Enhancing the Efficiency of Solar Desalination through Computational Fluid Dynamics (CFD) Modeling

Mayank Kumar[1], Dr. Ajay Singh[2], Prakash Sahu[3]

[1]*Scholar, Department of Mechanical Engineering, Radharaman Institute of Technology and Science, Bhopal, M.P*
[2] *Head and Prof., Department of Mechanical Engineering, Radharaman Institute of Technology and Science, Bhopal, M.P*
[3] *Assistant Professor, Department of Mechanical Engineering, Radharaman Institute of Technology and Science, Bhopal, M.P*

***

Abstract - *This research delves deep into using Computational Fluid Dynamics (CFD) to mimic how a single slope passive solar still works. The main aim was to create a detailed 3-D model of the solar still using ANSYS Workbench and compare what the simulation predicted with real-world experimental data. They carefully set up this virtual model in FLUENT, tweaking materials and environmental factors to mirror actual conditions and ran simulations for May 19th. Then, they checked how well the simulation matched the real data from Hassanain's experiments. Here's what they found: The CFD model they built did a great job at showing how temperatures spread within the solar still. The temperatures inside the still were very close to what they found in their experiments, proving the model's accuracy in capturing how heat behaves in the system. They also noticed that the glass temperature in the still followed the pattern of sunlight—it rose with solar intensity, hitting its highest point at around 337 Kelvin by 1:00 PM, then slowly dropped as the sun got weaker. Although the simulated results lined up well with the experimental data, there were some tiny differences. These variations happened because the simulated sunlight didn't perfectly match the real sun's intensity, and the model couldn't mimic natural adjustments like those that happen in real-world experiments. We used the CFD data to calculate how much water the still produced and how efficiently it transferred heat for evaporation using Dunkle's model. Luckily, the numbers they got from the simulations matched up impressively well with what they found in their experiments, proving that the CFD model could reliably predict what happens in real life. This study shows how powerful CFD simulations can be—they're like a crystal ball for understanding and improving passive solar stills. By digging into temperature dynamics and accurately predicting water output, this research pushes forward the quest to make solar-powered desalination more effective and eco-friendlier.*

Key Words Solar Still, Efficiency, CFD, Mesh, Temperature

1.INTRODUCTION

Freshwater scarcity is a growing concern in many regions of the world, driven by factors such as population growth, climate change, and increasing demands on limited water resources. Meeting the demand for clean and potable water in water-scarce areas is a critical challenge. In this context, solar stills have emerged as a sustainable and energy-efficient solution for addressing the pressing need for freshwater production. A solar still is a simple yet ingenious device that harnesses the power of the sun to desalinate and purify water. It operates on the principle of solar distillation, a process that replicates nature's own water purification cycle. By utilizing the sun's energy, solar stills offer a practical and environmentally friendly means of transforming brackish or contaminated water into safe, drinkable water. The operation of a solar still is relatively straightforward. It typically consists of a transparent cover or glazing, which allows sunlight to penetrate while trapping heat, and an inclined surface underneath to collect and direct the condensed water to a collection point. As sunlight passes through the transparent surface, it heats the contaminated or saline water present in the still's basin. This heat causes the water to evaporate, leaving behind impurities and salt. The water vapor rises, condenses on the glazing, and eventually drips down to the collection point as purified, distilled water. The collected freshwater is free from contaminants, making it safe for consumption. Solar stills are particularly valuable in regions where conventional sources of clean water are scarce or unreliable. They can be deployed in remote or off-grid areas, providing a decentralized solution to water purification needs. Furthermore, solar stills are powered by renewable energy sources, making them sustainable and cost-effective over the long term. The versatility of solar stills is evident in their ability to be scaled to meet the demands of both individual households and larger communities. They can be designed in various configurations, including single-slope, double-slope, and multi-effect stills, depending on the local climate, water quality, and water requirements. In this introduction, we embark on a journey to explore the world of solar stills. We will delve into the principles governing their operation, the various designs and configurations, the factors influencing their efficiency, and their applications in addressing water scarcity challenges. Solar stills represent a beacon of hope in the quest for sustainable and accessible freshwater solutions, offering a path towards a more water-secure and resilient future.

2. LITERATURE SURVEY

A study enhanced hemispherical distillate production by incorporating reflective mirror and aluminum foil, boosting solar radiation intensity. Results showed reflective aluminum foil sheets improved yield and efficiency by 42.3% and 37.5% respectively, while reflective mirrors showed a 62.6% increase in yield and a 57.26% efficiency boost compared to conventional distillers. Additionally, exergy efficiency saw a significant improvement, with cost reductions of 29% and 38% for reflective aluminum foil and mirrors, respectively, compared to the conventional setup [1]. An empirical study enhanced hemispherical solar distillers' cumulative yield using varying sizes of black gravel; the 16mm gravel size yielded the highest productivity of 7.7 kg/m^2/day, marking a 57.1% improvement over the reference distiller's 4.9 kg/m^2. This optimization demonstrated increased efficiency in distillation, showcasing a 56% improvement over the standard design [2]. This study explores enhancing freshwater production in rural areas by employing hemispherical solar distillers. Combining CuO nanoparticles and glass cover cooling technology significantly boosts productivity, yielding 7.9 L/m^2/day—105.2% higher than traditional distillers—and improving daily efficiency by 101.5% [3]. The study explores modifications to hemispherical solar distillers for enhanced productivity and cost-efficiency: one involves CuO nanoparticles in basin water for increased vapor generation, while the other uses water film glass cooling to improve condensation. Results show a significant increase in daily yield, up to 76.6%, and cost reduction to $0.0066/L, suggesting the most effective modification is the HSS-N (0.3% volume fraction) for optimal yield and cost-effectiveness [4]. An experiment enhanced the yield of a hemispherical solar distiller by incorporating a v-corrugated basin and reversed solar collector, elevating freshwater output by 68.82% and energy efficiency by 24.18%. The v-corrugated basin with reversed solar collector exhibited a 27.12% reduction in freshwater production cost compared to the traditional flat basin hemispherical distiller [5]. A study in Tanta, Egypt, enhanced a stepped solar distiller using CuO nanoparticles, interior mirrors, and phase change materials, boosting yield to 9.79 L/m^2/day—135.9% higher than the 4.15 L/m^2/day from the original design. The modified distiller raised daily thermal efficiency to 78.8% and exergy efficiency to 7.96%, proving the efficacy of the three hybrid optimizations for peak performance [6]. A study compared modified hemispherical solar stills (MHSS) using additives like paraffin wax and copper oxide nanoparticles to traditional ones (THSS), finding MHSS with PCM and CuO nanofluid increased productivity by up to 80.20% and enhanced daily energy efficiency from 35.52% (THSS) to 63.61%. Economically, the dual use of PCM and CuO nanofluid reduced freshwater production costs by 75% compared to THSS [7]. A study enhanced pyramid solar distillers with new modifications: CuO nano black paint, mirrors, and phase change material. Results showed a significant boost, elevating the yield to 9885–10015 mL/m2/day, marking a 140.1–142% improvement over the conventional distiller, with notable enhancements in daily thermal and exergy efficiencies [8]. A study enhanced tubular solar stills with copper hollow fins and PCM for improved water production. Results showed 90.1% productivity improvement with hollow circular fins and PCM. Another study on pyramid solar distillers showed a 140.1–142% yield increase using a novel combination of modifications including CuO nano black paint, reflective mirrors, and phase change materials with pin fins [9]. This study explores enhancements for solar distillers, testing reflective elements and sand grains to optimize productivity. Results showed a significant increase in distillate production, reaching 9400 mL/m2/day with reflective mirrors and sand grains, presenting a cost-effective solution, reducing freshwater production costs by 49.1% compared to the conventional distiller [10]. A study on hemispherical solar desalination found that a water flow rate of 2.5 L/h optimally cooled the glass cover, enhancing distiller performance by achieving a 43.61% yield increase (5.17 L/m2/day) and 50.7% daily efficiency compared to a conventional setup. This optimized flow rate also yielded the shortest payback period in the techno-economic analysis compared to other systems tested [11]. An experimental study enhanced hemispherical distillers' performance using El Oued sand grains, determining 3% concentration as optimal, boosting yield to 7270 mL/m2/day (52.1% increase) and daily efficiency to 59.1% (50.8% improvement). This involved testing eight concentrations in modified distillers over four days, showcasing the significant enhancement over the traditional reference distiller, which achieved an accumulative yield of 4780 mL/m2/day and 39.2% daily efficiency [12]. The manuscript explores optimizing graphite concentration in hemispherical distillers, determining 35g/L as the ideal concentration, achieving a 93.94% improvement in yield and 91.66% in daily efficiency compared to the reference distiller. The study underscores that exceeding 35g/L of graphite in high thermal conductivity storage materials stabilizes productivity, suggesting no need for higher concentrations, saving resources and time [13]. The study investigates a modified solar still using sandbags as energy storage, showcasing a 34.57% increase in distillate yield (5.06 L/m^2/d) compared to traditional solar still (3.76 L/m^2/d), employing El Oued sand with high thermal conductivity (97.6% quartz and 0.56% calcite), thus enhancing daily efficiency by 34.83% (44.63% for MSS-SB versus 33.1% for TSS) under similar climatic conditions in southeast Algeria [14]. The study explores rock salt balls as a low-cost solution to minimize heat loss in hemispheric solar stills. Results suggest that a 4.0 cm gap spacing of these balls maximizes freshwater production by up to 49.0%, significantly enhancing energy efficiency and reducing costs by 31.0% per liter compared to conventional setups [15]. An experimental study enhances freshwater output in hemispheric solar distillers by embedding spherical rock salt balls for better heat absorption and cost-efficient energy storage. Findings show a 45.6% increase in freshwater production, 43.91% higher energy efficiency, and up to 28.83% reduced production costs, with 2.0 cm salt balls proving most effective in improving distillatory performance [16]. This paper reviews three types of solar air collectors (FPSAC, EVTSAC, and concentrated SAC), aiming for high efficiency and low heat loss. Findings show FPSACs with specific designs achieve a performance criterion of about 2, EVTSACs with micro-heat pipe arrays reach 73% thermal efficiency, and concentrated SACs can achieve a 75% thermal efficiency with a linear concentrating design using an open Brayton cycle, highlighting the need for high-efficiency heat transfer components in SAC design [17]. This paper explores the factors affecting pyramid solar still performance, highlighting meteorological, design, and operational aspects. Enhanced designs, such as PCM integration, v-corrugated plates, reflectors, mirrors, and nanoparticle utilization, can elevate productivity by up to 88%, emphasizing the crucial role of climatic and structural elements, prompting suggestions for future research to optimize solar distillation [18]. A mathematical model using response surface methodology predicts optimal conditions for pyramid solar distillers (PSD) considering environmental factors and nanoparticle variations, showcasing a substantial increase in daily productivity (57% for Cu2O-PSD) compared to conventional PSD. Experimental validation demonstrates a high reproducibility rate (within 6.5% error) between actual and predicted values, affirming the model's reliability [19].

3. METHODDOLOGY AND CFD

3.1 Design of Heat Exchanger

Solar still is basically an insulated metallic box covered by an inclined transparent glass. A schematic diagram of the single slope passive solar still is shown in the figure 3.2. Solar still contains a shallow basin which is made up of GI sheet. The basin area is 0.8 m ×1.0 m. Still is constructed as a double walled body and a thick thermocol sheet is sandwiched between the GI sheet walls in order to insulate the basin. The inner basin area of solar still is painted black in order to increase its absorptivity. Mirrors are placed on the inner side walls of the basin to reflect the solar radiation towards the bottom surface of the basin. A 5 mm thick transparent glass cover is placed over the solar still. The glass cove is inclined at an angle of 260 towards south which is the latitude angle of Bhopal.

3.2 Meshing

Following the creation of the geometric model, the subsequent critical step in CFD analysis is the generation of the computational mesh for the problem domain. Meshing involves dividing the domain into a multitude of small cells. Within each of these cells, the CFD software conducts calculations to simulate the physical phenomena under examination. The number of cells within the domain significantly influences the outcomes of the simulation. It is imperative that the number of cells is sufficiently large to accurately capture the intricacies of the physical processes being modelled. However, it's important to strike a balance, as an excessive number of cells can extend the solver's computational time, potentially making simulations impractical. Therefore, there is an ongoing quest to determine the optimum number of cells that can yield sufficiently accurate results while maintaining a reasonable computation time. The determination of this optimum cell count is not one-size-fits-all; it varies based on the complexity of the problem at hand and the available time for simulations. More complex problems may require a denser mesh, while simpler scenarios can make do with a coarser mesh. Ultimately, finding this balance is a crucial aspect of efficient and effective CFD analysis.

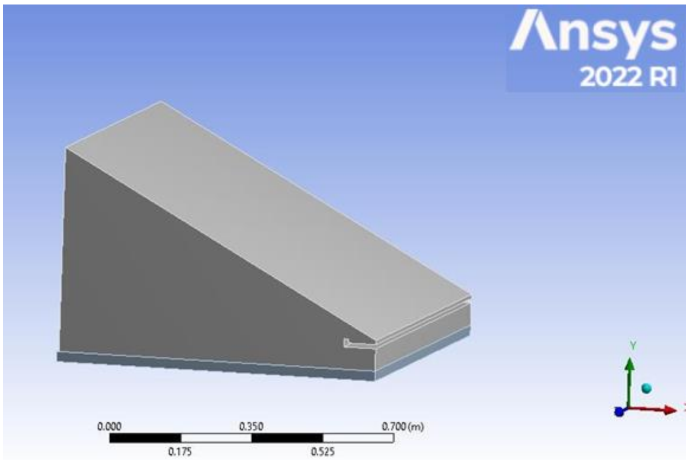

Figure 1 Geometric Model of the solar still

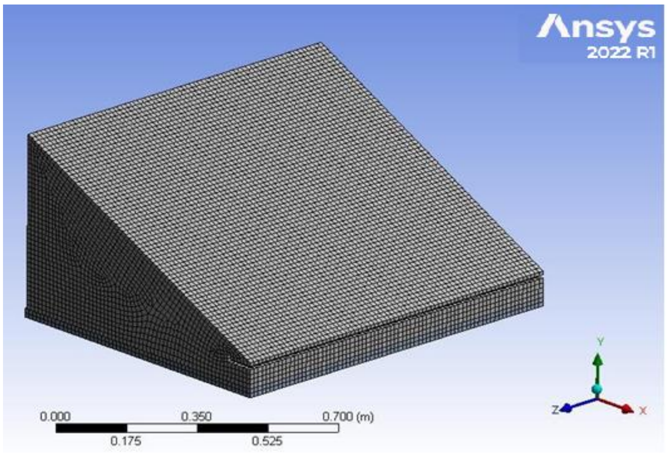

Figure 2 Meshing of the computational domain

The importance of a high-quality mesh cannot be overstated when it comes to ensuring the accuracy of CFD analysis. In this particular study, after an extensive literature review, the decision was made to employ a hexahedral mesh for discretization. Hexahedral elements were used exclusively in the meshing process due to the specific characteristics of the solar still's geometry. Notably, the solar still's geometry primarily comprises rectangular surfaces, devoid of any curved elements. This fact makes hexahedral meshing exceptionally well-suited for the task, as it is known to deliver precise results while maintaining a reasonable computation time.

3.3 Boundary Condition

Defining proper boundary types and boundary conditions is essential for the accurate solution for a fluid flow problem. Most of the boundary conditions are determined by the physical phenomena but some are set by the simulation software. In this section, the type of boundary condition for each of the physical boundaries of the solar still domain is explained. Table 1 shows the boundary types and boundary conditions for various parts of the geometric model.

Table 1 Boundary types and boundary conditions

Zone name	Zone Type	Description	Heat Generation Rate (W/m³)	wall Thickness(m)
front_wall	Wall	Adiabatic wall (Heat flux = 0)	-	0
back_wall	Wall	Adiabatic wall	-	0
side_wall_1	Wall	Adiabatic wall	-	0
side_wall_2	Wall	Adiabatic wall	-	0
glass	Wall	Convection losses	-	0
bottom_wall	Wall	Adiabatic wall	-	0

3.4 Selection of Turbulence Model

Turbulence flows are characterized by chaotic motion of fluid particles. It is generally characterized in terms of irregularity, diffusivity, large Reynolds numbers, three-dimensional vorticity fluctuations, dissipation and continuum. Turbulence models are needed to solve unknown variables. The correct analysis of the problems involving turbulence is the biggest challenge in CFD modeling. No single turbulence model can be universally applied to all situations. Certain considerations must be taken into account while choosing an appropriate turbulence model for any problem. Important considerations in this regard are physics involved in the flow problem, desired level of accuracy and the availability of the computational resources.

4 RESULTS AND DISCUSSION

4.1 Temperature Profile

In case of solar still, temperatures attained by glass cover, water in the basin and the interior of the still play vital role for the distillation of water. In general, amount of distillate produced by solar still depends upon the temperature difference between water in the basin and glass cover. Temperature contours inside the solar still are drawn at the X-Y plane passing through Centre of the still and parallel to its side walls. Temperature profiles of interior temperature and the glass temperature are shown at different time intervals. In the temperature contours a common range from 314 K to 360 K for temperature was chosen for appropriate representation of the contours.

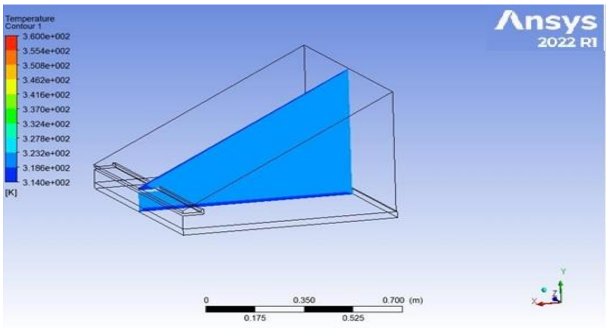

Figure 3 Contour of interior temperature at 09:00 hrs

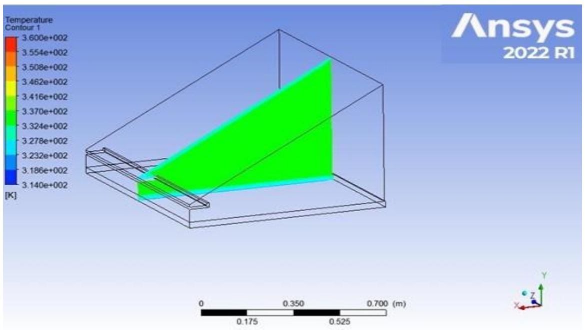

Figure 4 Contour of interior temperature at 10:00 hrs

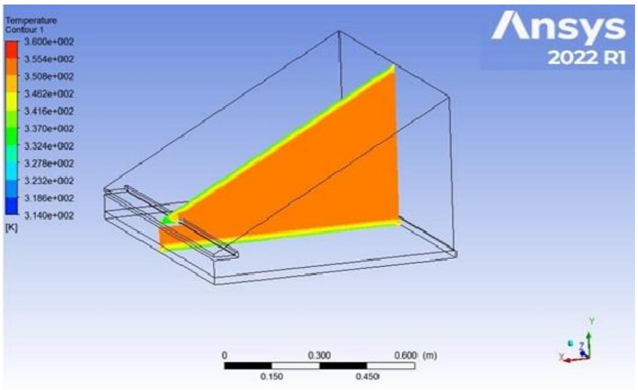

Figure 5 contour of Interior temperature at 12:00 hrs

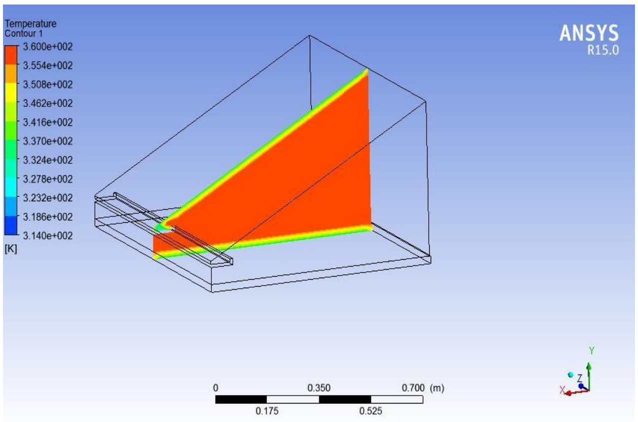

Figure 6 contour of Interior temperature at 14:00 hrs

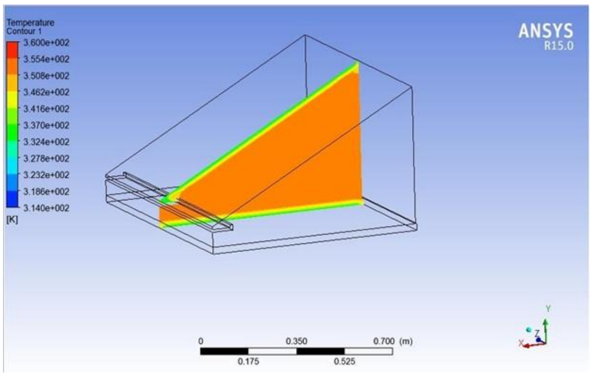

Figure 7 contour of Interior temperature at 16:00 hrs

The contours of interior temperature of solar still show that: -

- Within the solar still the temperature of water begins to rise as the solar radiations falls in the basin. After some time, water gets heat up and evaporation takes place which results in the vapor formation in the still as well as increase in the interior temperature. Contours of interior temperature show the increment in the interior temperature of solar still with time.

- The temperature inside the solar still increases as the intensity of solar radiation increases. Interior temperature of still increases monotonically up to 13:00 hrs and after that it decreases monotonically. Basically, the interior temperature of the still follows the pattern of solar radiation falling over the glass cover.

- It is clear from the contours of interior temperature that temperature of the mixture is almost uniform in the still. This is because after one hour of operation the hot vapors have acquired almost all the space in the still.

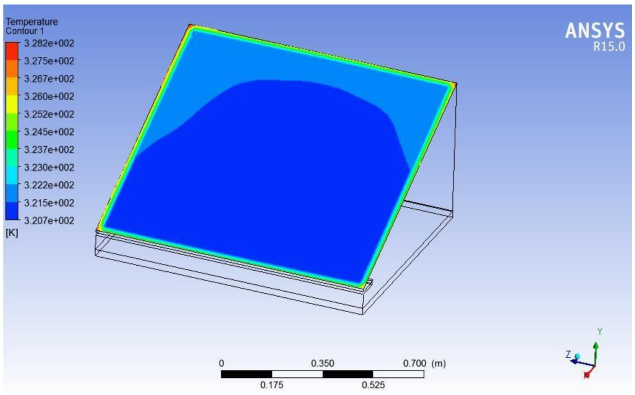

Figure 8 Glass temperatures at 10:00 hrs

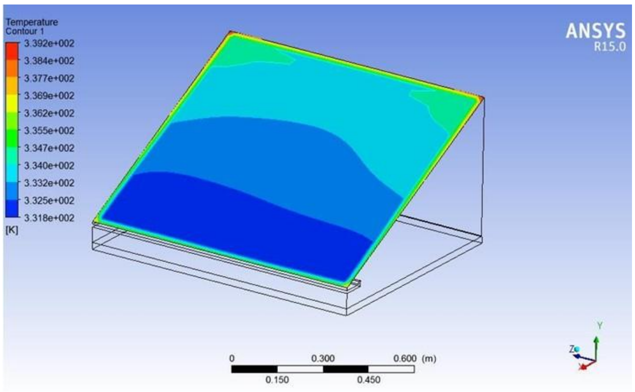

Figure 9 Glass temperatures at 12:00 hrs

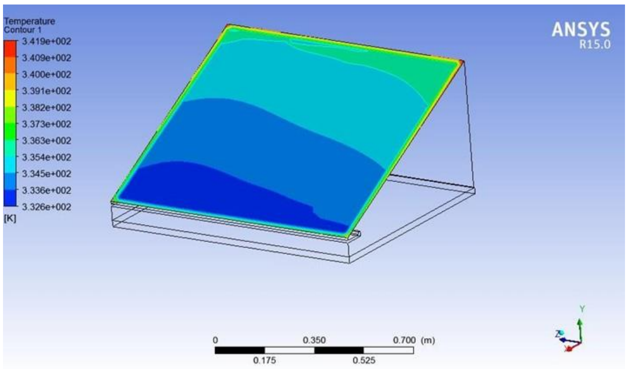

Figure 10 Glass temperatures at 14:00 hrs

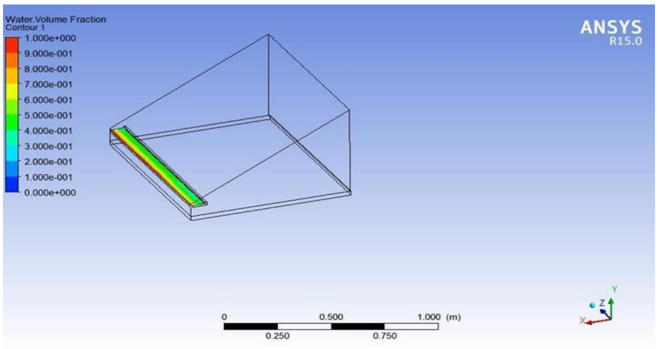

Figure 11 Glass temperatures at 17:00 hrs

From the contours of glass cover temperatures, it can be noticed that the temperatures on the lower end of glass cover are relatively lesser than the temperature at the upper part of the glass cover. This is due to the fact that distilled water slides down on the inside of glass cover from the upper part to the lower end of the glass cover.

- Figure 12 shows the contour of water volume fraction at the distillate channel. Water volume fraction in distillate channel is nearly 0.7 which indicates that the distillate water gets accumulated in the channel after sliding down from the tilted glass surface.

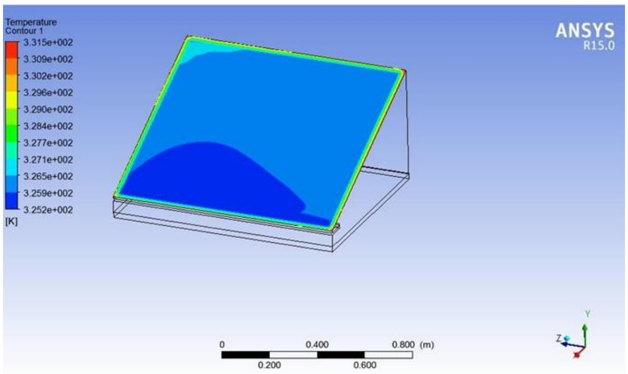

Fig 12 Contour of water volume fraction at the distillate channel

5 CONCLUSIONS

The main objective of this study was to develop a 3-D CFD model of a single slope passive solar still and to compare the simulation results with the available experimental results. First the 3-D geometric model of solar still was developed in ANSYS Workbench through design modeler. Then appropriate models were selected for the physical phenomena occurring in the solar still. Material properties and appropriate boundary conditions were defined in Fluent for the simulation of the problem. Simulations were carried for unsteady state conditions with FLUENT solver for 19th May. The simulation results were compared with the experimental results taken by Hassanain.

The main conclusions of the study are as follows: -

- The present CFD model is able to simulate the temperature at various points in the solar still. The simulated values of interior temperatures are in agreement with the experimental values.

- The glass temperature follows the similar trend as that of solar radiations. It increases with the solar intensity reaching a maximum value of about 337 K at 13:00 hrs and then it starts decreasing due to the decreasing value of solar intensity

- Although the simulated results follow the same trend as the experimental results yet there is a slight difference between the two-temperature data. The difference between the two values is most likely due to the difference in solar intensity for two cases and also because of the fact that simulated values do not take into consideration for natural attenuations that occur in real experiments.

- The rate of distillate water output and evaporative heat transfer coefficient are calculated on the basis of Dunkle 's model using CFD data. There is a good agreement between the simulated and experimental data for distillate yield.

REFERENCES

[1] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., Abdullah, A., 2021. A comparative study of the effect of internal reflectors on a performance of hemispherical solar distillers: energy, exergy, and economic analysis. Sustainable Energy Technologies and Assessments 47, 101465. https://doi.org/10.1016/j.seta.2021.101465.

[2] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., Abdel-Aziz, M.M., Bellila, A., Abdullah, A., 2021. Optimal size of black gravel as energy storage materials for performance improvement of hemispherical distillers. Journal of Energy Storage 43, 103196. https://doi.org/10.1016/j.est.2021.103196.

[3] Attia, M.E.H., Kabeel, A.E., Elaloui, E., Abdelgaied, M., Abdullah, A., 2022. Experimental study on improving the yield of hemispherical distillers using CuO nanoparticles and cooling the glass cover. Solar Energy Materials and Solar Cells 235, 111482. https://doi.org/10.1016/j.solmat.2021.111482.

[4] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., Abdelaziz, G.B., 2021. A comparative study of hemispherical solar stills with various modifications to obtain modified and inexpensive still models. Environmental Science and Pollution Research 28 (39), 55667–55677. https://doi.org/10.1007/s11356-021-14862-x.

[5] Kabeel, A.E., Attia, M.E.H., Zayed, M.E., Abdelgaied, M., Abdullah, A.S., El- Maghlany, W.M., 2022. Performance enhancement of a v-corrugated basin hemispherical solar distiller combined with reversed solar collector: An experimental approach. Renewable Energy 190, 330–337.

[6] Abdelgaied, M., Abdulla, A.S., Abdelaziz, G.B., Kabeel, A.E., 2022. Performance improvement of modified stepped solar distillers using three effective hybrid optimization modifications. Sustainable Energy Technologies and Assessments 51, 101936. https://doi.org/10.1016/j.seta.2021.101936.

[7] Abdelgaied, M., Attia, M.E.H., Kabeel, A.E., Zayed, M.E., 2022. Improving the thermo-economic performance of hemispherical solar distiller using copper oxide nanofluids and phase change materials: Experimental and theoretical investigation. Solar Energy Materials and Solar Cells 238, 111596. https://doi.org/10.1016/j.solmat.2022.111596.

[8] Abdelgaied, M., Kabeel, A.E., 2021. Performance improvement of pyramid solar distillers using a novel combination of absorber surface coated with CuO nano black paint, reflective mirrors, and PCM with pin fins. Renewable Energy 180, 494–501. https://doi.org/10.1016/j.renene.2021.08.071.

[9] Abdelgaied, M., Zakaria, Y., Kabeel, A.E., Essa, F.A., 2021. Improving the tubular solar still performance using square and circular hollow fins with phase change materials. Journal of Energy Storage 38, 102564. https://doi.org/10.1016/j. est.2021.102564.

[10] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., Shmouty, A.R., 2022. Enhancing the hemispherical solar distiller performance using internal reflectors and El Oued sand grains as energy storage mediums, Environmental Science. Pollution Research 29, 21451–21464. https://doi.org/10.1007/s11356-021-17367-9.

[11] Attia, M.E.H., El-Maghlany, W.M., Kabeel, A.E., Abdelgaied, M., Bellila, A., 2022. Technically and economically optimal water flow rate glass film cooling for hemispherical drinking water distillers. International Journal of Environmental Science and Technology 19 (11), 11435–11446.

[12] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., 2021. Optimal concentration of El Oued sand grains as energy storage materials for enhancement of hemispherical distillers performance. Journal of Energy Storage 36, 102415. https://doi.org/ 10.1016/j.est.2021.102415.

[13] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., Bellila, A., Abdel-Aziz, M.M., 2021. Optimal concentration of high thermal conductivity sensible storage materials (graphite) for performance enhancement of hemispherical distillers. Desalination and Water Treatment 231, 262–272. https://doi.org/10.5004/dwt.2021.27479.

[14] Attia, M.E.H., Kabeel, A.E., Abdelgaied, M., Driss, Z., 2020. Productivity enhancement of traditional solar still by using sandbags of El Oued-Algeria. Heat Transfer 50 (1), 768–783. https://doi.org/10.1002/htj.21903.

[15] Attia, M.E.H., Kabeel, A.E., Zayed, M.E., Abdelgaied, M., Sharshir, S.W., Abdulla, A.S., 2022. Experimental study of a hemispherical solar distillation system with and without rock salt balls as low-cost sensible storage: Performance optimization and comparative analysis. Solar Energy 247, 373–384. https://doi. org/10.1016/j.solener.2022.10.049.

[16] Attia, M.E.H., Kabeel, A.E., Zayed, M.E., Arıcı, M., Abdelgaied, M., 2022. Optimal size of spherical rock salt balls as low-cost thermal storage materials for performance augmentation of hemispherical solar distillers: Experimental investigation and thermo-economic analysis. Journal of Cleaner Production 374, 134006. https://doi.org/10.1016/j.jclepro.2022.134006.

[17] Zhang, J., Zhu, T., 2022. Systematic review of solar air collector technologies: Performance evaluation, structure design and application analysis. Sustainable Energy Technologies and Assessments 54, 102885. https://doi.org/10.1016/j. seta.2022.102885.

[18] Hammoodi, K.A., Dhahad, H.A., Alawee, W.H., Omara, Z.M., 2023. A detailed review of the factors impacting pyramid type solar still performance. Alexandria Engineering Journal 66, 123–154. https://doi.org/10.1016/j.aej.2022.12.006.

[19] Farouk, W.M., Abdullah, A.S., Mohammed, S.h.A., Alawee, W.H., Omara, Z.M., Essa, F.A., 2022. Modeling and optimization of working conditions of pyramid solar still with different nanoparticles using response surface methodology, Case Studies. Thermal Engineering 33, 101984. https://doi.org/10.1016/j. csite.2022.101984.