Computational Fluid Dynamics Simulation of Thermal Parameters for Desalination in a Single-Slope Solar Still

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Abstract
Water is a vital component of life that is abundantly available on planet Earth. However, a significant amount of the world's water is not fit for direct use and drinking due to salinity and contaminants. Salinity coupled with the impacts of population growth, industrialization, climate change, and pollution has led to the decreasing supplies of safe drinking water. The desalination process has emerged as a decisive solution to meet the increasing demand for potable water. The distillation process particularly through a solar still, has gained importance for the purity of salty and contaminated water using solar energy. Solar stills have the potential to solve the problem of drinking water, especially in remote areas and villages. A simulation-based study has been conducted to analyze the desalination process in a single slope solar still using ANSYS Fluent in Peshawar, Pakistan (coordinates: 34.0151°N, 71.5249°E). The study is focused on investigating the various parameters including glass temperature, water temperature, heat transfer coefficient, and volume fraction of water and vapors. The simulation results illustrate the significance of various parameters influencing the performance of the solar still and provide crucial information about the temperature profile and condensation formation, which plays a vital role in the overall efficiency of the desalination process within the solar still.

Keywords: CFD, Solar still, Heat transfer coefficient, Temperature, Volume fraction

Introduction
Water is an imperative component of life and irreplaceable for the survival of human life and all other living species. The cutting-edge revolution in the industrial sector and the worldwide population growth have extremely contaminated the earth's environment for a long time and thus the water quality is gravely influenced. The quest to conveniently transport clean water is continually expanding due to population growth and increasing demand. Due to the non-availability of affordable electricity, fossil fuels, and lack of resources in remote rural communities, expensive and commercial desalination strategies to get clean water cannot be utilized, so in such regions, the utilization of sun-based still is the best alternative. Sun power has risen as the best alternative to be used in remote towns to arrange clean potable water. Solar still as shown in Figure 1, is an immovable device that utilizes heat energy from the sun to produce clean water. It could be a cheap and green gadget, contamination-free, and has no natural dangers.

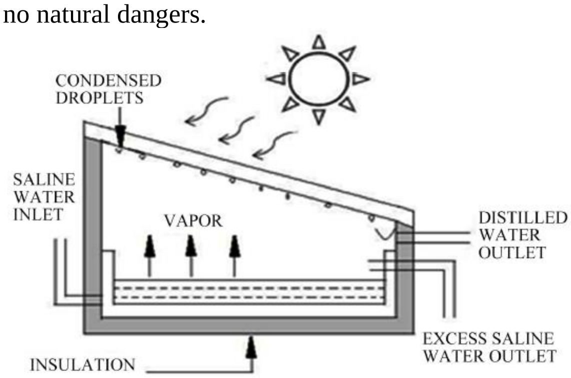

Figure 1. **Schematic of single basin solar still [1]**.

Experiments were conducted to extensively evaluate various parameters during water distillation using passive solar still [1]. An extensive paper on CFD modeling of solar still to investigate the effect of various parameters on the productivity of solar still has been published by Keshtkar [2]. Mahmoud et al. [3] published an extensive review on increasing the productivity of solar still using thermoelectric material, highlighting that the electric materials improved the performance of solar still. Shahin et al. [4] worked on different techniques to enhance evaporation and condensation rates in solar stills. Different designs and techniques have been reviewed and summarized to increase the water production rate and lower the cost of solar still [3, 5-12]. Mittal et al. [13] conducted unsteady Computational fluid dynamics (CFD) on single-slope solar stills using ANSYS Fluent. Their study involved specifying the glass temperature at the top and the water temperature at the bottom. They considered a humid zone, which comprises a mixture of water vapor and air. The evaporation and condensation rates were calculated at the top condensing surface by utilizing the vapor mass fraction. Sheron et al. [14] in a separate study focused on hybrid-type solar still design that occupies less space and considered the local climatic conditions of India to investigate various parameters. They modeled the still to study the effect of various parameters and thermodynamically analyzed it. The parameters that were investigated include water depth, feed rate, shade, and absorber area. Narjes et al. [15] determined the heat transfer coefficient of solar still using CFD. A two-phase, three-dimensional model was developed for the condensation and evaporation process using computational fluid dynamics to simulate the model. Gnanavel et al. [5] worked on improving the productivity of solar still using phase change material. Instead of using water and glass temperature as a boundary condition, Keshtkar et al. [16] proposed an innovative approach for CFD modeling of solar still utilizing irradiance and meteorological data as inputs. Agrawal et al. [17] in their study calculated the heat transfer coefficient and examined the productivity of solar still by conducting experimental and theoretical studies in the climatic conditions of India finding such a technology very suitable for the region. Prakash et al. [18] made a review to investigate the effect of various parameters influencing the performance of solar stills. The effect of factors improving productivity such as water depth, water and glass temperature,

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area of heat absorption, inlet water temperature, etc. were discussed. Tiantong et al. [19] investigated the effects of geometrical and operating parameters on the performance of tubular solar still using computational fluid dynamics. Rahbar et al. [20] worked on tubular solar still to investigate heat and mass transfer using computational fluid dynamics. Mohammad et al. [21] studied the impact of solar radiation intensity on the productivity of solar still. A thorough assessment of recent numerical research on several types of solar still including single-slope solar still, double-slope solar still, tubular, and a few others was provided by Mojtaba et al. [22]. The study showed that many investigations can be done using CFD analysis of solar stills. Milad et al. [23] explored a transient model of the solar still in which the thermal inertia of components, aspect ratio of evaporation space, salinity level, and bulk water were considered. Saman et al. [24] simulated condensation and evaporation phenomena in solar stills by applying a volume of fluid method and improving its productivity by incorporating Al_2O_3-water nanofluid. Alvarado et al. [25] numerically studied the conjugate heat and mass transfer phenomena in solar still. Kunal et al. [26] explored various operational parameters impacting the performance of the still by simulating a multiphase,3D model of the still. In their study, an absorber plate covered with nanoparticles was considered. An in-depth examination of the literature reveals that a significant amount of work has been done on experimental studies of solar still but limited research has been done on CFD analysis and simulation-based studies, particularly for Pakistani climate. The flexibility of CFD as a tool allows researchers to change various parameters and input factors providing an excellent to study the impact of various factors on the performance of solar stills. Through CFD researchers can potentially enhance the performance of solar still and can improve water production rate. The current study is based on a two-phase, 3D model of a solar still designed using ANSYS workbench, allowing analysis and simulation of complex interaction of vapor, water, and solar still structure. The study can contribute to more efficient and productive solutions for the global freshwater scarcity challenge.

Mathematical model description

The first step to solving any problem using CFD involves the creation of a mathematical model of the problem area. In this study, a three-dimensional, two-phase model was developed using the volume of the fluid model. The VOF model was applied to simulate a mixture of air, water, and water vapor systems under steady-state conditions. Since evaporation occurs only at the surface, the interface between water and vapor is considered for modeling purposes. For simulation and analysis, the phenomena of evaporation and condensation are used. The equation of continuity, energy, and mass transfer relations have been considered in this work. For each phase, all the equations were solved numerically [27]. A summary of the governing equations is presented in this section;

Continuity;

$$\frac{\partial \boldsymbol{\rho}}{\partial \mathbf{t}} + \boldsymbol{\nabla}.\boldsymbol{\rho}\vec{\mathbf{v}} = \mathbf{0} \tag{1}$$

Where $\vec{v}$ s is the time average velocity vector and ρ is density.

Momentum;

To model the natural convection in the air vapor gap, the density in the air-water vapor mixture is considered as a function of temperature. The momentum equation is described by eq. k-epsilon RNG turbulence model is used to calculate shear stress $(\vec{\tau}_{eff})$.

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.\rho\vec{v}\vec{v} = -\nabla P + \nabla.(\vec{\tau}_{eff}) + \rho\vec{g} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.\rho\vec{v}\vec{v} = -\nabla P + \nabla.(\vec{\tau}) + \rho\vec{g}\beta(T - T_o) \tag{3}$$

Energy;

The energy equation solved in each layer of the solar still is given by

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(\vec{v}(\rho E + P)) = \nabla.(\lambda_{eff}\nabla T - \textstyle\sum_j h_{Ej}\vec{J}_j) + S_h + S_L \tag{4}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(\vec{v}(\rho E + P)) = \nabla.(\lambda\nabla T) + S_h + S_L \tag{5}$$

Where h_{Ej} and $\vec{J}_j$ are the sensible enthalpy and diffusive flux of species j and λ_{eff} is the effective thermal conductivity obtained by k-epsilon RNG turbulence model;

$$\frac{\partial}{\partial t}(\rho E) = \nabla.(\lambda\nabla T) + S_h + S_L \tag{6}$$

S_h is the absorbed radiant energy and S_L is the latent heat of evaporation or condensation.

Heat Transfer Coefficient Analysis;

In this study, Dunkle's correlation has been employed to calculate the heat transfer coefficient from glass to water. The equation used for calculating the heat transfer coefficient is given below.

$$h_{cw} = 0.884[T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{268900 - P_w}]^{\frac{1}{3}} \tag{7}$$

where

$$P_w = \exp\left(25.317 - \frac{5144}{T_w + 273}\right) \tag{8}$$

and

$$P_g = \exp\left(25.317 - \frac{5144}{T_g + 273}\right) \tag{9}$$

For finding heat transfer due to convection the equation used is given below:

$$q_{cw} = h_{cw}(T_w - T_g) \tag{10}$$

Simulation strategy and boundary conditions

To solve a CFD problem and get an accurate solution defining proper boundary types and boundary conditions is important. Boundary conditions are defined according to the problem and physical phenomena. Boundary conditions for each physical boundary of the solar still domain in this work including walls, glass, and bottom are explained. Boundary types and conditions for the geometric model are shown in Table 1.

In CFD analysis, the first step to solving any problem is the creation of the geometry of the problem domain according to the design specification. A 3D model of a single solar still was designed using Space claim in ANSYS workbench. After that mesh was generated for the computational domain. The schematic of the geometry along with its mesh and dimensions is shown in Figures 2 and 3 for the single slope solar still. The solar still fundamentally consists of a protected metallic box with an inclined transparent glass cover [1]. The bottom region of the still is a shallow bowl made of a GI sheet. The dimensions of the shallow bowl are

1.0 m × 1.0 m. For better insulation, the still is designed as a double-walled structure with a thermocol sheet sandwiched between the walls made of GI sheet. To enhance the absorption of solar radians the inner basin area of the solar still is coated with black paint. Additionally, mirrors are placed on the inner side walls of the basin in such a way as to reflect maximum solar radiations toward the bottom of the still. A transparent glass cover of 5mm thickness is placed at the top of the still. The glass cover is placed at an angle of 19.73°.

Table 1: Boundary types and boundary conditions

Zone name	Zone type	Wall thickness (meters)	Condition
Absorber	Wall	0.025	Adiabatic wall
Glass cover	Wall	0.025	Convection losses
Front wall	Wall	0.025	Adiabatic wall
Back wall	Wall	0.025	Adiabatic wall
Side walls	Wall	0.025	Adiabatic wall

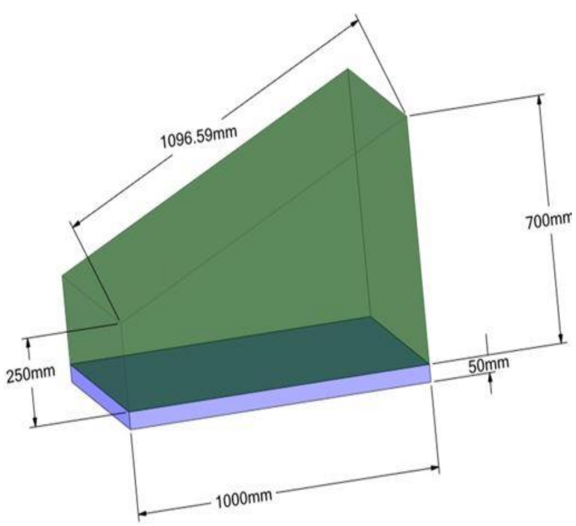

Figure 2. The geometry of single-slope solar still.

Mesh independence study

The mesh independence test is an important concept in computational fluid dynamics and is conducted to check if the solution obtained is independent of mesh resolution. In the current work, a mesh independence test was done to find the optimal mesh size that best represents heat transfer coefficient and temperature within solar still in the shortest possible time with compromising accuracy.

For mesh independence analysis in the current study, several mesh and cell sizes from coarse to fine have been simulated. The number of nodes in the coarse, medium, and fine mesh is taken as 15246, 24375, and 46080 respectively while the number of cells is 13440, 21888, and 42253.

Simulation results for the temperature of basin water for the three types of mesh sizes are shown in Figure 4. Since the results do not vary with mesh refinement, the current simulations and analysis are thus regarded as mesh-independent. The optimal mesh size adopted for further investigation in the current CFD simulation is medium size with 21888 cells.

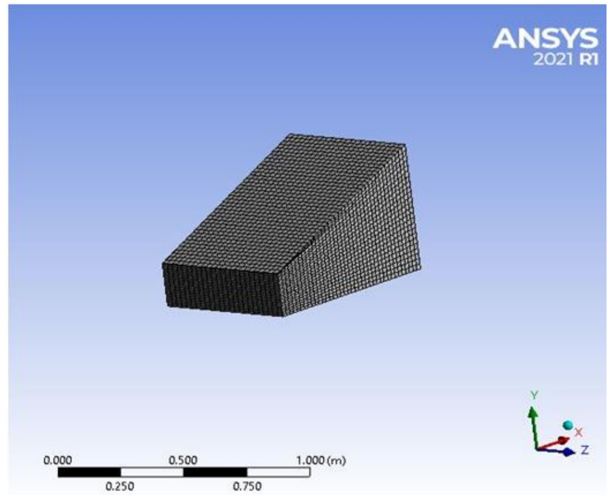

Figure 3. Mesh of single-slope solar still.

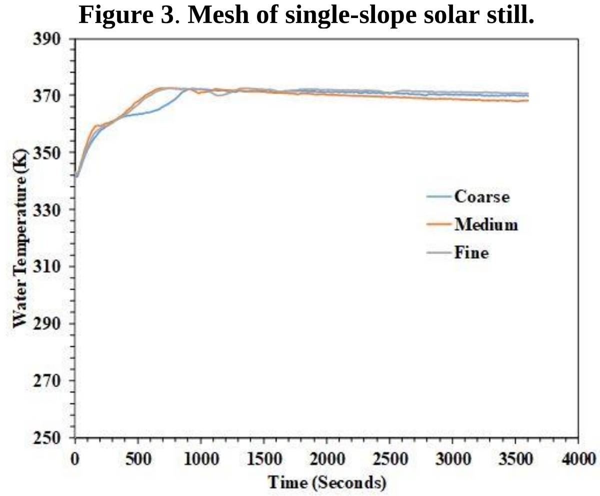

Figure 4. Water temperature for the coarse, medium, and fine mesh schemes for grid independence.

Simulation results

In this study, the simulation results for the solar still using CFD have been obtained and illustrated in the form of different graphs and contour plots of volume fraction, temperature distribution, and heat transfer coefficient in the subsequent section. For July, transient simulations of solar still have been conducted covering a period from 7:00 to 16:00 hrs. Temperature values, volume fraction of water phase, vapor phase, and heat transfer coefficient in the form of contours have been presented.

The distillation of water in the solar still is greatly influenced by the temperature of basin water, glass cover, and temperature distribution inside the solar still. The output of distill water production is directly affected by the temperature difference between the glass cover and basin water. To illustrate the temperature at different time intervals, temperature contours are drawn for the solar still, giving an insight into temperature distribution across various parts of the solar still.

Figure 5 presents a contour plot of temperature distribution in the solar still at 8:00 hrs. At this time, the temperature is high at the glass cover and gradually increases within the still and at the bottom as time progresses.

Figure 6 illustrates the contour of temperature distribution at noon, revealing a noticeable change in temperature as compared to 8:00 hrs, as evident from temperature values and color patterns. This temperature change is because at 12:00 hrs solar intensity and heat flux are greater when compared to 8:00 hrs.

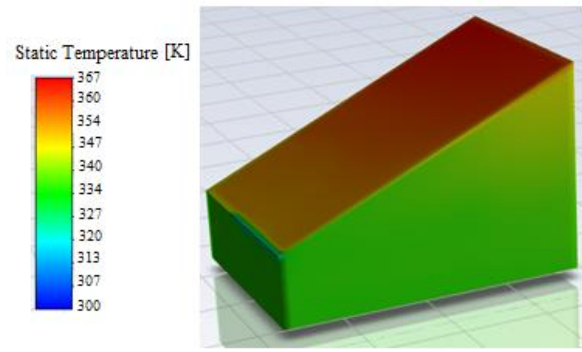

Figure 5. The contour of temperature distribution in the solar still at 8:00 hrs.

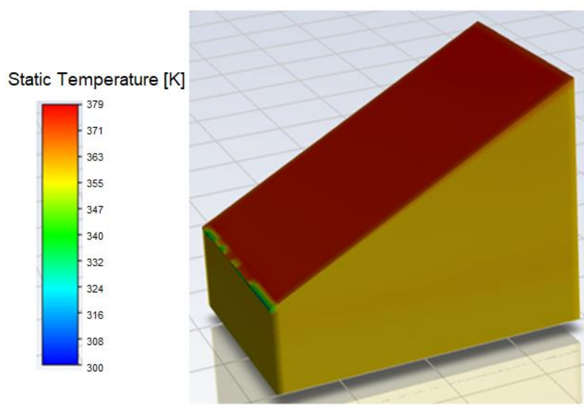

Figure 6. The contour of temperature distribution in the solar still at 12 o'clock in the noon.

The volume fraction of water and vapor plays a crucial role in desalination. Higher vapor formation contributes to high volume fraction and greater production of distillate. The vapor formation is influenced by both the temperature distribution at the bottom of the still and solar radiations falling onto the still. The contours showing the volume fraction in solar still are presented at various time intervals.

In Figure 7, the contour illustrates the volume fraction of vapor in solar still at 8:00 hrs in the morning, after one hour of operation. It is evident from contours that as the temperature of basin water increases over time, there is a noticeable increase in vapor formation.

In Figure 8, the volume fraction vapor at 13:00 hrs is shown. It is evident from the figure that a significant portion of the still is occupied by the vapors. As time passes, the vapor condenses and transforms into distilled water. Similarly, figure 9 illustrates a contour plot of the volume fraction of water.

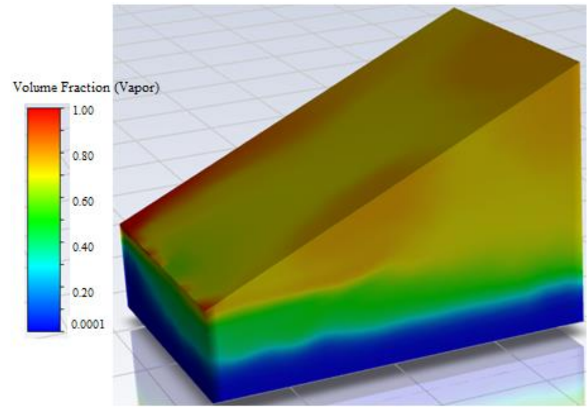

Figure 7. The contour of the volume fraction of vapor in the solar still.

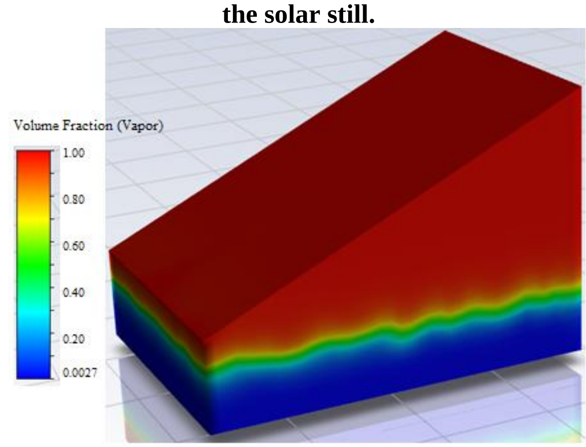

Figure 8. The volume fraction of vapor at 13:00 hrs.

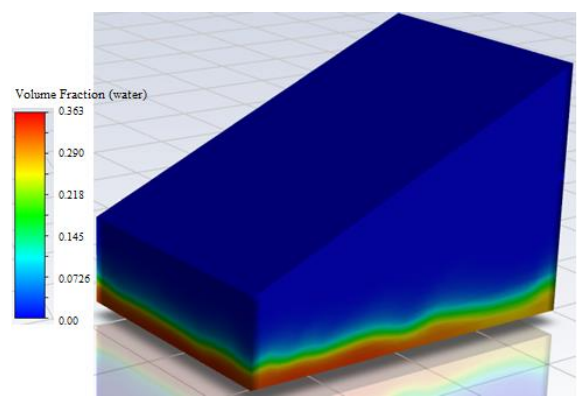

Figure 9. The volume fraction of water at 13:00 hrs.

Figure 10 shows the variation in temperature of basin water at different time intervals of the day. Basin water temperature has a direct impact on the performance of solar still because with an increase in basin water temperature evaporate rate increases exponentially and hence increases the productivity of solar still. It has been observed that the intensity of solar radiation varies directly with time, reaching its peak value at

13:00 hrs. During morning hours from 7:00 to 8:00 hrs, the average water temperature remains relatively low i.e. 88.40 °C. As a result, a high amount of energy is required to change its phase from saturated liquid to saturated vapor. The atmospheric temperature is also minimum in the early morning and it gradually increases after the sun rises. As the day passes, the average water temperature reaches its peak value in the early afternoon. From 12:00 to 13:00 hrs the average water temperature stands approximately at 96.17°C while in the late afternoon from 15:00 to 16:00 hrs the average water temperature reaches 93.27 °C. The temperature difference between glass cover and basin water is maximum in the afternoon hence evaporation rate increases exponentially and solar still has maximum productivity at that time of the day.

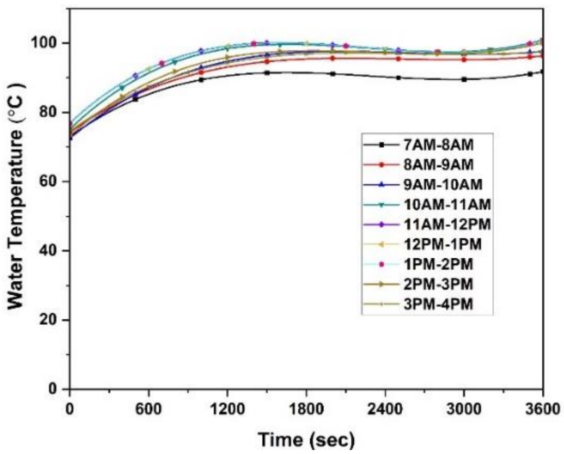

Figure 10. Variation of water temperature at different time intervals during the day.

Figure 11, illustrates how the volume fraction of vapor varies at different times of the day. It is evident from the figure that the volume fraction reaches its peak value around 13:00 hrs, which corresponds to the time when the temperature within the still is maximum. On average, the volume fraction is approximately 0.8 at 13:00 hrs which shows that a high amount of vapors is present in the still. However, after 13:00 hrs volume fraction of vapor gradually starts decreasing as the temperature value decreases in the later part of the day.

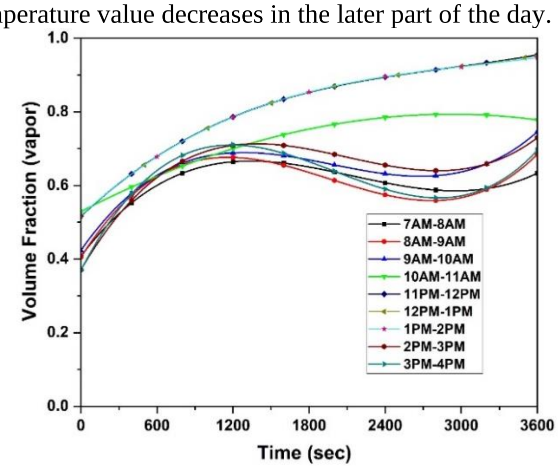

Figure 11. Variation of volume fraction of vapor with time.

Figure 12 illustrates how the heat transfer coefficient varies at different times of the day. As time passes, the temperature distribution and solar radiation increase, reaching their maximum values between 11:00 to 14:00 hrs. Thereafter, the intensity of solar radian falling over the still decreases and the temperature within the still also gradually decreases. In the morning when the temperature within the still is low so heat transfer coefficient at around 8:00 h reaches a maximum of 2.46. The results show that in the afternoon around 13:00hrs the heat transfer coefficient reaches the maximum value of 9.8 $\frac{W}{m^2K}$ while in the late afternoon around 16:00hrs the heat transfer coefficient reaches a maximum value of 4.6. Heat transfer coefficient plays a significant role in performance optimization and productivity improvement of solar still.

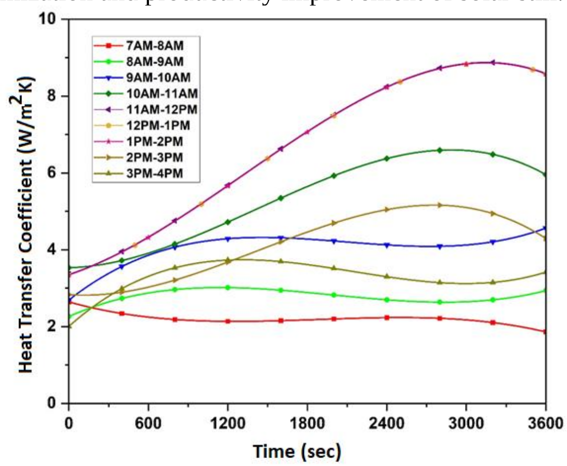

Figure 12. Variation of heat transfer coefficient with time

Conclusion

This study uses ANSYS Fluent to develop a 3D model of a single-slope solar still. The simulations were conducted to analyze various parameters of the still. A 3D geometric model of the solar still was created using ANSYS space claim, followed by selecting appropriate models according to the physical phenomena taking place in the still. Proper materials properties and boundary conditions were defined in ANSYS fluent for accurate simulation of the problem. Simulations were conducted for July in the Peshawar region and results were obtained, considering average solar radiations, ambient temperature, and solar heat flux. Based on the results obtained, the following conclusions can be drawn:

1. From 11:00 to 14:00 hrs, the temperature reaches its maximum value within the still, as a result, maximum heat transfer occurs in the still and the heat transfer coefficient value reaches its peak within this period.
2. From 7:00 hrs, the volume fraction of vapor gradually starts increasing and reaches its highest value around 14:00 hrs, after that it gradually starts decreasing.
3. Between 11:00 to 14:00 hrs, the solar still achieves maximum efficiency.
4. Solar radiations directly impact the temperature and volume fraction of vapor within the still. Higher solar radiation contributes to high temperatures and increases vapor volume.

Overall, the study provides valuable insights into the behavior and performance of single-slope solar still under different operating conditions during July in a specific region.

Acknowledgment

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Conflict of Interest

The authors declare that they have no conflict of interest.

Abbreviations

The following abbreviations are used in this paper:

T_g is Glass temperature [K]
T_v Vapor temperature [K]
T_w Water temperature [K]
ε K.E. dissipation rate
ω Specific dissipation rate $[s^{-1}]$
∇ Gradient operator
T Temperature [K]
P Pressure [kPa]
P_w Saturation pressure at water temperature [kPa]
P_g Saturation pressure at glass temperature [kPa]
Q Heat transfer from various surfaces [kJ]
h_{cw} Convective Heat transfer coefficient $\left[\frac{W}{m^2 K}\right]$
K Thermal conductivity [W/m K]
k Turbulent kinetic energy [kJ/kg]
I Solar intensity $\left[\frac{W}{m^2}\right]$

References

1. Gnanadason, M. K.; Kumar, P. S.; Wilson, V. H., Heat and Mass Transfer and Thermo Physical Analysis of Water Distillation Using Passive Solar Still. *Smart Grid and Renewable Energy* **2020,** 11, (6), 73-87.
2. Keshtkar, M.; Eslami, M.; Jafarpur, K., Effect of design parameters on performance of passive basin solar stills considering instantaneous ambient conditions: a transient CFD modeling. *Solar Energy* **2020,** 201, 884-907.
3. Elgendi, M.; Kabeel, A.; Essa, F., Improving the solar still productivity using thermoelectric materials: A review. *Alexandria Engineering Journal* **2022**.
4. Shoeibi, S.; Rahbar, N.; Esfahlani, A. A.; Kargarsharifabad, H., A review of techniques for simultaneous enhancement of evaporation and condensation rates in solar stills. *Solar Energy* **2021,** 225, 666-693.
5. Gnanavel, C.; Saravanan, R.; Chandrasekaran, M., CFD analysis of solar still with PCM. *Materials Today: Proceedings* **2021,** 37, 694-700.
6. Hota, S. K.; Hada, S. S.; Keske, C.; Diaz, G., Feasibility of desalination by solar stills for small community scale freshwater demand. *Journal of Cleaner Production* **2022,** 379, 134595.
7. Jamil, F.; Hassan, F.; Shoeibi, S.; Khiadani, M., Application of advanced energy storage materials in direct solar desalination: a state of art review. *Renewable and Sustainable Energy Reviews* **2023,** 186, 113663.
8. Javadi, F. S.; Metselaar, H. S. C.; Ganesan, P., Performance improvement of solar thermal systems integrated with phase change materials (PCM), a review. *Solar Energy* **2020,** 206, 330-352.
9. Sakthivadivel, D.; Balaji, K.; Dsilva Winfred Rufuss, D.; Iniyan, S.; Suganthi, L., Chapter 1 - Solar energy technologies: principles and applications. In *Renewable-Energy-Driven Future*, Ren, J., Ed. Academic Press: 2021; pp 3-42.
10. Saxena, A.; Cuce, E.; Kabeel, A. E.; Abdelgaied, M.; Goel, V., A thermodynamic review on solar stills. *Solar Energy* **2022,** 237, 377-413.
11. Shalaby, S. M.; Hammad, F. A.; Zayed, M. E., Current progress in integrated solar desalination systems: Prospects from coupling configurations to energy conversion and desalination processes. *Process Safety and Environmental Protection* **2023**.
12. Sikiru, S.; Oladosu, T. L.; Amosa, T. I.; Kolawole, S. Y.; Soleimani, H., Recent advances and impact of phase change materials on solar energy: A comprehensive review. *Journal of Energy Storage* **2022,** 53, 105200.
13. Mittal, G., An unsteady CFD modelling of a single slope solar still. *Materials Today: Proceedings* **2021,** 46, 10991-10995.
14. Sharon, H., Energy, exergy, environmental benefits and economic aspects of novel hybrid solar still for sustainable water distillation. *Process Safety and Environmental Protection* **2021,** 150, 1-21.
15. Setoodeh, N.; Rahimi, R.; Ameri, A., Modeling and determination of heat transfer coefficient in a basin solar still using CFD. *Desalination* **2011,** 268, (1-3), 103-110.
16. Keshtkar, M.; Eslami, M.; Jafarpur, K., A novel procedure for transient CFD modeling of basin solar stills: Coupling of species and energy equations. *Desalination* **2020,** 481, 114350.
17. Agrawal, A.; Rana, R.; Srivastava, P. K., Heat transfer coefficients and productivity of a single slope single basin solar still in Indian climatic condition: Experimental and theoretical comparison. *Resource-Efficient Technologies* **2017,** 3, (4), 466-482.
18. Prakash, P.; Velmurugan, V., Parameters influencing the productivity of solar stills–A review. *Renewable and sustainable energy reviews* **2015,** 49, 585-609.
19. Yan, T.; Xie, G.; Liu, H.; Wu, Z.; Sun, L., CFD investigation of vapor transportation in a tubular solar still operating under vacuum. *International Journal of Heat and Mass Transfer* **2020,** 156, 119917.
20. Rahbar, N.; Esfahani, J. A.; Fotouhi-Bafghi, E., Estimation of convective heat transfer coefficient and water-productivity in a tubular solar still–CFD simulation and theoretical analysis. *Solar Energy* **2015,** 113, 313-323.
21. Esfe, M. H.; Esfandeh, S.; Kamyab, M. H.; Toghraie, D., Simulation of the impact of solar radiation intensity on the performance of economical solar water desalination still in Semnan province. *Case Studies in Thermal Engineering* **2021,** 28, 101471.

22. Edalatpour, M.; Aryana, K.; Kianifar, A.; Tiwari, G.; Mahian, O.; Wongwises, S., Solar stills: A review of the latest developments in numerical simulations. *Solar Energy* **2016,** 135, 897-922.
23. Mohsenzadeh, M.; Aye, L.; Christopher, P., Development and validation of a transient model for a passive solar still considering the aspect ratio of the evaporation chamber. *Solar Energy* **2022,** 244, 434-447.
24. Rashidi, S.; Akar, S.; Bovand, M.; Ellahi, R., Volume of fluid model to simulate the nanofluid flow and entropy generation in a single slope solar still. *Renewable Energy* **2018,** 115, 400-410.
25. Alvarado-Juárez, R.; Álvarez, G.; Xamán, J.; Hernández-López, I., Numerical study of conjugate heat and mass transfer in a solar still device. *Desalination* **2013,** 325, 84-94.
26. Bansal, K.; Kumar, R.; Mishra, S. K.; Kumar, P.; Sharma, A., Validation and CFD modeling of solar still with nanoparticle coating on absorber plate. *Materials Today: Proceedings* **2022,** 63, 673-679.
27. Fluent, A., ANSYS Fluent 2021 R1 user's guide and theory manual'. *Ansys Fluent Inc* **2021**.