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THERMAL PERFORMANCE AND CFD VALIDATION OF A STAINLESS-STEEL SOLAR STILL FOR WATER DESALINATION

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Abstract

Clean and safe drinking water is one of the basic necessities for human survival. However, the quantity of usable freshwater available on Earth is extremely limited. Increasing contamination of natural water resources has further intensified the global demand for affordable purification technologies. Solar desalination is considered an environmentally sustainable approach because it utilizes solar energy to convert saline or contaminated water into potable water. Among different desalination systems, solar stills are widely preferred due to their low operating cost, simple construction, and eco-friendly operation.

The present investigation focuses on the experimental analysis of a square-type single-slope solar still fabricated from SS-304 stainless steel. The experimental observations were compared with Computational Fluid Dynamics (CFD) simulations performed using ANSYS Fluent. The variation between basin water temperature and glass cover temperature was considered as the primary validation parameter. Numerical results were found to be in close agreement with the experimental values, with deviations ranging between 0.22% and 20.80%. The vapor distribution and thermal behavior inside the still were also analyzed using CFD techniques.

Keywords

Solar desalination, CFD analysis, ANSYS Fluent, SS-304 solar still, potable water

1. Introduction

Water is an essential requirement for the existence and survival of all living organisms. Although nearly 71% of the Earth's surface is covered with water, only a very small portion, less than 1%, is available as usable freshwater suitable for drinking and agricultural purposes [1]. The growing demand for clean water has increased the importance of desalination technologies as a practical solution for producing potable water from saline sources [2]. However, many conventional desalination techniques require high energy input derived from non-renewable resources, making them expensive and difficult to implement in economically weaker or remote regions. In addition, continuous contamination of natural freshwater resources has created severe environmental and public health concerns worldwide [3].

Solar desalination through a solar still provides an environmentally sustainable and economical alternative for water purification. A solar still operates on the principle of the natural hydrological cycle [4], where solar radiation heats the saline water inside a closed basin, leading to evaporation. The generated water vapor condenses on the cooler inner surface of a transparent glass cover, while impurities such as dissolved salts and heavy metals remain in the basin. The condensed water is then collected as purified freshwater. Owing to its simple construction, low maintenance requirement, and eco-friendly operation, the solar still is considered highly suitable for rural and off-grid locations. The performance of a solar still depends on several parameters including weather conditions, design configuration, and operating characteristics. Continuous advancements in solar energy applications and material technologies are further improving the efficiency and practicality of solar still systems.

2. Review of Literature

Research aimed at improving the productivity of solar stills has mainly concentrated on modifying absorber surfaces and incorporating heat-absorbing materials. Different absorber materials such as aluminum and galvanized iron plates [5], blackened copper fins [6], and several alternative configurations [7] have been investigated by researchers. Another important approach involves the application of dyes and colored absorber coatings. For example, the use of black naphthylamine dye resulted in nearly 29% enhancement in distillate yield [8]. Similar improvements were observed with violet dye [13] and blackened sponge layers of varying thicknesses [9]. In addition, porous media and packed bed materials have shown promising results in improving evaporation rates. The placement of sand at the basin bottom increased productivity by approximately 75% [10], while materials such as sandstone and marble pieces were also experimentally examined [11, 18].

The incorporation of advanced materials and hybrid enhancement techniques has further improved the thermal performance of solar still systems. Researchers have explored the use of nanoparticles such as Al_2O_3, SnO_2, and ZnO [14], along with graphite and copper oxide nanoparticles [15]. Likewise, nanofluids including SiO_2/water and Cu/water mixtures [16] demonstrated noticeable improvements in system efficiency. Additional enhancement methods include the integration of concentrators with phase change materials (PCM) like paraffin wax [12], evacuated tube collectors (ETC) [20], and the use of both internal and external reflectors [19]. Modifications in basin configuration, particularly double basin solar stills, produced nearly 36% higher output compared to conventional single basin designs [21]. Techniques such as glass cover cooling [17] and the use of jute cloth as an energy storage medium [22] have also contributed to improved freshwater productivity.

In recent years, Computational Fluid Dynamics (CFD) has become an important tool for the simulation and optimization of solar still systems. Software packages such as ANSYS Workbench and FLUENT have been widely employed for conducting parametric studies, estimating heat transfer coefficients, and validating experimental observations. These numerical techniques have proven highly effective for analyzing heat and mass transfer phenomena within solar stills and for improving their design and operational performance [23, 24, 25, 26].

A conventional solar still has been modified by many researchers in different ways to improve its freshwater yield. The productivity of a solar still mainly depends on the temperature difference between the basin water surface and the inner glass cover, where a larger temperature difference results in higher distillate output. In the present investigation, experimental analysis of a solar still has been carried out and the obtained results have been validated through ANSYS-CFD simulations.

3. Experimental Setup

A square-shaped, single-slope, single-effect solar still with an effective basin area of 0.85 m² (920 mm × 920 mm) was designed and fabricated using 1 mm thick SS-304 stainless steel sheets through CNC bending and argon welding processes. A transparent glass cover of 5 mm thickness was installed at an inclination angle of 20° to facilitate condensation of water vapor. The complete assembly was supported on a metal stand to maintain adequate clearance from the ground surface. To reduce thermal losses from the basin to the surroundings, 6 mm thick polyethylene foam insulation was provided around the system. An internal SS-304 collection channel was incorporated to collect the condensed distillate and direct it towards an external storage flask. Figure 1 illustrates the actual experimental setup of the fabricated SS-304 solar still.

Figure 1- Photograph of a SS-304 solar still

Experimental investigations were carried out for five continuous days at Gadhinglaj, Kolhapur, Maharashtra, India (16.2264440° N, 74.3499680° E). The experiments were conducted daily between 09:00 hrs and 18:00 hrs under outdoor climatic conditions. Prior to the start of each experiment, the basin of the solar still was filled with 20 liters of normal river tap water at 08:30 hrs. A stabilization period of 30 minutes was maintained before recording the observations.

A Data Acquisition (DAQ) system was connected to the setup for automatic monitoring and recording of experimental parameters at intervals of 30 minutes. Solar radiation intensity (S) was measured using a pyranometer having an operating range of 0–2000 W/m² with an accuracy of ±3%. Different temperature locations were monitored using digital temperature sensors operating within a voltage range of 0–5.5 V and having an accuracy of ±0.5°C.

The parameters measured during the experimentation included solar irradiance (S) in W/m², basin water surface temperature (T1 in °C), saturated vapor temperature (T2 in °C), inner glass cover temperature (T3 in °C), outer glass surface temperature at the center (T4 in °C), basin base temperature (T5 in °C), and ambient temperature (T6 in °C). Table 1 presents the maximum daily solar irradiance values recorded during the experimental period along with the corresponding temperature readings and freshwater productivity obtained from the SS-304 solar still.

Table 1- Experimental Daily Peak Parameters and Productivity of the SS-304 Solar Still

Date	**T1 °C**	**T2 °C**	**T3 °C**	**T4 °C**	**T5 °C**	**T6 °C**	**Solar Irradiance (W/m^2)**	**Daily Productivity ($l/m^2/day$)**
Dec 23,2023	58.46	62.51	57.51	59.13	33.38	33.72	764.62	1.647
Dec 24,2023	59.63	63.14	58.09	58.78	33.72	34.06	767.23	1.729
Dec 25,2023	57.88	64.40	59.25	59.96	34.39	34.74	772.48	1.831
Dec 26,2023	65.06	70.27	64.65	65.20	37.02	37.40	792.89	1.910
Dec 27,2023	61.98	66.94	61.59	62.33	35.75	36.11	779.98	1.871

The observations listed in Table 1 reveal that the productivity of the solar still increases with an increase in solar irradiance. A direct relationship between solar intensity and freshwater output was clearly observed during the experimental investigation. On 26 December 2023, the system recorded the maximum solar irradiance value of 792.89 W/m^2, which resulted in the highest distillate productivity of 1.910 $l/m^2/day$.

The productivity values obtained during the experimentation correspond to winter climatic conditions, under which the tests were conducted. During this season, lower solar altitude angles and comparatively reduced solar insolation decrease the overall heat energy available for evaporation, thereby limiting the freshwater yield of the solar still.

4. ANSYS-CFD Analysis

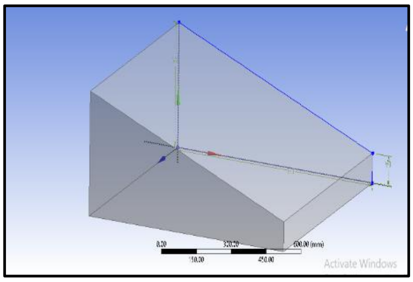
A three-dimensional (3D) model of the single-slope solar still was created using ANSYS Design Modeler, as illustrated in Fig. 2. To reduce computational complexity and simulation time, unnecessary geometric details were excluded from the model. The developed geometry was then exported for mesh generation. A structured mesh with refined elements near the important heat transfer regions was generated, as shown in Fig. 3. To ensure reliable numerical accuracy, a mesh independence study was performed before finalizing the mesh configuration. Based on the study, a mesh element size of 9 mm was selected for further analysis. Linear structural meshing with medium smoothing was adopted, resulting in a total of 782040 elements and 815184 nodes.

The thermo-physical properties of all materials considered in the simulation were specified appropriately. Water was assigned a density of 997 kg/m^3, specific heat capacity of 4182 J/kg·K, and thermal conductivity of 0.6 W/m·K. Air properties were defined as density 1.225 kg/m^3, specific heat capacity 1006 J/kg·K, and thermal conductivity 0.0242 W/m·K. The thermal conductivity values of SS-304 stainless steel, polyethylene insulation, and glass cover were taken as 16.2 W/m·K, 0.33 W/m·K, and 1.05 W/m·K respectively.

Suitable boundary conditions were applied for different regions of the computational domain. Heat flux and constant temperature conditions were assigned to the basin wall to simulate the effect of solar heating. Convective heat transfer conditions were imposed on the glass cover to represent cooling by surrounding air. The insulation walls were treated as adiabatic surfaces. Ambient conditions were maintained at atmospheric pressure of 1 atm and temperature of 25°C.

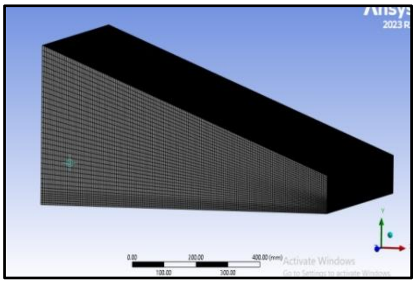
The numerical simulation was carried out in ANSYS Fluent using a pressure-based transient solver to capture the time-dependent thermal behavior inside the solar still. The k-ε turbulence model was selected for modelling turbulent flow characteristics, while the radiation model was used to account for solar radiation effects. The Volume of Fluid (VOF) multiphase model was employed to track the interaction between air and water phases within the enclosure.

The initial water temperature was considered as 25°C, and the initial fluid velocity throughout the domain was assumed to be zero. A transient time step of 1 second was used during the simulation, with a total simulation duration of 4 hours to study the thermal response of the system. Convergence criteria for continuity, momentum, and energy equations were fixed at 1×10^{-6}. The solution process was continuously monitored for convergence, and all simulations were executed on a high-performance computing (HPC) system to minimize computational time and ensure stable numerical performance.



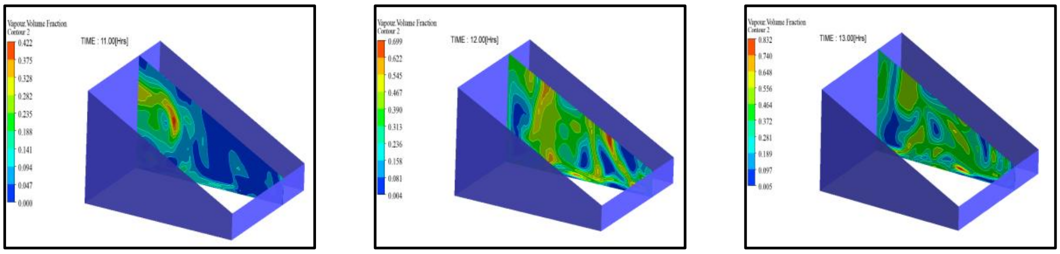
(a)

Figure 2 - A 3D model



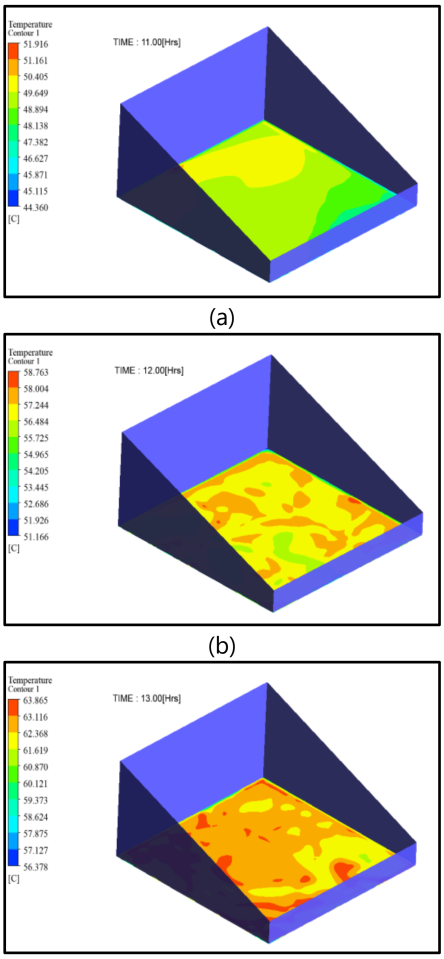
(b)

Figure 3 - Meshing of the geometry



(a) (b) (c)

Figure 4 - Volume fractions of vapor observed through CFD analysis for (a) 11.00 hours, (b) 12.00 hours and (c) 13.00 hours respectively

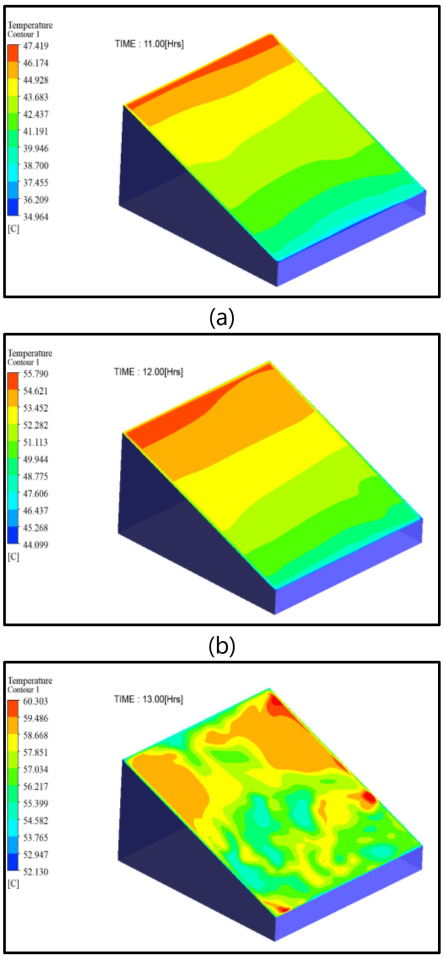


(a)

(b)

(c)

Figure 5 - Temperature contours for the temperature of water surface inside the basin for (a) 11.00 hours, (b) 12.00 hours and (c) 13.00 hours respectively



(a)

(b)

(c)

Figure 6 - Temperature contours for the temperatures of glass outer surface for (a) 11.00 hours, (b) 12.00 hours and (c) 13.00 hours respectively

Figure 4 (a, b, c) shows the volume fraction of vapor for 11.00, 12.00 and 13.00 hours respectively observed through CFD analysis. Figure 5 (a, b, c) and Figure 6 (a, b, c) shows the temperature contours for the temperature of water surface inside the basin (T1) 0C and for temperatures of glass outer surface (T4) 0C for 11.00, 12.00 and 13.00 hours respectively.

The CFD analysis indicated a gradual rise in both the basin water temperature and the glass cover temperature as the simulation progressed with time. At 13:00 hours, the maximum temperature of the water surface inside the basin reached 63.86°C, whereas the outer glass cover temperature attained 60.30°C. Furthermore, the vapor volume fraction inside the solar still showed a continuous increase from 0.422 at 11:00 hours to 0.832 at 13:00 hours. This increase in vapor concentration confirms the effective evaporation and condensation processes occurring within the solar still during peak solar radiation conditions.

5. Results and Discussion

The following Table 2 describes the validation of experimental and computational results. It can be stated that a close agreement between experimental and computational analysis was observed, confirming the accuracy of the output. Further the volume fraction of vapor increases as the solar radiation increases.

Table 2 - Validation of results for SS-304 solar still

Sr	Time	Volume Fraction of Vapor	Parameters	SS-304 Solar Still		
				Experimental	Computational	% difference
1	11.00	0.422	• Temperature of water surface inside the basin (T_1) ^{0}C	42.13	51.91	20.80
			• Temperature of glass outer surface- centre (T_4) ^{0}C	42.36	47.41	11.25
2	12.00	0.699	• Temperature of water surface inside the basin (T_1) ^{0}C	52.58	58.76	11.01
			• Temperature of glass outer surface- centre (T_4) ^{0}C	52.87	55.79	5.37
3	13.00	0.832	• Temperature of water surface inside the basin (T_1) ^{0}C	59.84	63.86	6.50
			• Temperature of glass outer surface- centre (T_4) ^{0}C	60.17	60.30	0.22

6. Conclusions

- The mesh independence study ensured the accuracy of the simulation, with an optimal mesh size of 9 mm.
- The use of turbulence modelling (k-ε) and the Volume of Fluid (VOF) multi-phase model effectively captured the complex fluid dynamics and heat transfer phenomena.
- The validation of CFD results with experimental data confirmed the reliability of the computational approach.
- A close agreement between experimental and computational analysis was observed with percentage differences ranging from 0.22 % to 20.80 %.
- This study highlights the effectiveness of CFD as a tool for optimizing solar still designs, reducing the need for costly experimental testing, and improving system performance.

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