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CFD Analysis of Solar Still with Different Inclination Angle

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ABSTRACT

The increasing demand for clean and sustainable freshwater resources has intensified research on solar desalination systems, particularly solar stills. This study presents a Computational Fluid Dynamics (CFD) analysis and optimization of a single-slope solar still to improve its thermal performance and freshwater productivity. Three-dimensional CAD models of the solar still were developed using ANSYS Design Modular software. The CFD analysis was performed using a Multiphase Volume of Fluid (VOF) model incorporating air, liquid water, and water vapor phases. Evaporation-condensation mechanisms and solar radiation effects were included to simulate realistic operating conditions for the geographical location of Bhopal, India (Longitude 77.40°E, Latitude 23.25990°N). The study investigated the influence of key parameters such as slope angle and glass thickness on mass flow rate, basin temperature, and distillate productivity. Taguchi optimization techniques were employed to determine the optimal operating configuration. The results demonstrated that slope angle significantly affects mass flow rate, while glass thickness has a major impact on productivity enhancement. The optimized configuration, consisting of a 30° slope angle and 0.03 m glass thickness, showed superior thermal performance compared to the conventional design. Under optimized conditions, productivity increased from 221.73 ml/hr to 293.52 ml/hr, indicating a substantial improvement in freshwater yield. The findings confirm that proper optimization of geometrical and operational parameters can considerably enhance solar still efficiency without increasing system complexity.

Keywords: Solar still, CFD analysis, Single-slope solar still, Inclination angle, Glass thickness, Taguchi optimization, Volume of Fluid (VOF), Desalination, Freshwater productivity, Thermal performance.

1. INTRODUCTION

A solar still is a device that purifies water by utilizing solar energy to drive evaporation and condensation processes. Various types of solar stills exist, including large-scale concentrated systems and simple condensation traps, commonly referred to as moisture traps among survivalists. In a typical solar still, impure water is placed outside the collection area and heated by sunlight passing through a transparent cover such as glass or plastic [1–3]. As the water evaporates, the vapor condenses on the cooler inner surface of the cover and is collected as distilled water [4].

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This process closely replicates the natural hydrological cycle. Solar energy heats water bodies, causing evaporation; the vapor rises, cools, and condenses to form precipitation. Similarly, in a solar still, impurities such as salts, heavy metals, and microorganisms are left behind during evaporation, resulting in pure distilled water [5–8].

Solar stills are particularly useful in situations where conventional water sources—such as rainwater, piped supply, or groundwater—are unavailable or unreliable. These include remote areas and regions affected by natural disasters or power outages [9–11]. In subtropical regions prone to hurricanes and extended power failures, solar distillation provides a reliable alternative source of potable water. Several condensation collection techniques have been developed to enhance efficiency [12].

Access to potable water is essential not only for sustaining life and environmental balance but also for supporting agricultural and industrial activities. However, freshwater scarcity has become a major global issue due to increasing pollution of rivers and lakes from industrial discharge, as well as rapid population growth. According to global reports, more than 1.1 billion people lack access to safe drinking water, and approximately 1000 children die daily due to diseases caused by contaminated water. In water-scarce regions, this shortage may even contribute to conflicts [1]. The availability of fresh water is therefore recognized as one of the most critical challenges facing humanity.

Several advanced desalination technologies have been developed, such as multi-stage flash (MSF), multiple-effect distillation (MED) [2], thermal vapor compression (TVC) [3], membrane distillation (MD) [4], and reverse osmosis (RO) [5]. Although effective, these methods require significant energy input and skilled personnel for operation. In contrast, many regions with limited energy resources receive abundant solar radiation throughout the year, making solar-based solutions more feasible.

A solar still is a simple and widely used technology for converting brackish or saline water into potable water. It can be constructed using locally available materials and requires minimal maintenance [6]. Despite these advantages, basin-type solar stills generally suffer from low productivity. To address this limitation, researchers worldwide have proposed various design improvements and modifications to enhance performance. These include single- and double-slope solar stills [7], single-slope double-basin configurations [8], fin-type designs [9], the use of thermal storage materials such as rubber and glass balls [10,11], and the incorporation of external reflectors [12].

Furthermore, solar stills have been integrated with other systems such as flat plate collectors, solar ponds, and concentrators to improve productivity. While these approaches can significantly enhance output, they often increase the overall system cost [13]. Therefore, a key challenge lies

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in improving the productivity of solar stills without compromising their inherent advantage of low cost.

This challenge can be addressed by optimizing the various parameters that influence solar still performance. Such optimization requires detailed modeling of heat and mass transfer processes within the system. Computational Fluid Dynamics (CFD) modeling plays a crucial role in this regard, as it enables the simulation of evaporation and condensation phenomena while allowing flexible variation of design and operating parameters. This approach significantly reduces the time and cost associated with extensive experimental investigations for parameter optimization.

2. PAST STUDIES

Kanka et al. (2024) [19] reviewed the published articles pertaining to the incorporation of various performance enhancing approaches into direct SSs for the generation of fresh drinking water, including nanoparticles, nano-PCM, hybrid nanoparticles, fins, and sponges. Reviewing the publications findings indicates that the production of fresh water is greatly increased by using hybrid nanoparticles and copper balls with PCM (4460 ml/-day).

Sathyamurthy et al. (2024) [20] investigated a solution by enhancing a single slope solar still (SSSS) with paraffin wax as an energy storage medium in recycled soda cans. These cans were coated with a unique mixture of black paint and carbon soot nanoparticles gathered from automobile engine exhausts to boost thermal conductivity and heat absorption. These nanoparticles, averaging 50–60 nm in size, greatly enhanced the heat absorption efficiency of the cans. Morphological examination demonstrated a consistent distribution of nanoparticles across the surfaces of the cans.

Afolabi et al. (2023) [21] analyzed double slope solar still (DSSS) integrated with PCM-TES is presented. PCM was microencapsulated with epoxy resin composite using vacuum mould-filled techniques. Conventional DSSS and DSSS-TES data collected have been compared to establish the influence of TES on productivity. Daily average temperature of the glass cover, humid air, saline water, still basin absorber and TES cavity for the DSSS-TES attained are 65.2 °C, 77.5 °C, 82.4 °C, 79.5 °C and 68.4 °C, respectively. DSSS-TES has yielded higher production, with 7.5 Litres of potable water daily and extension in operation period by 3 h has been achieved. In addition, condensation and evaporation rates increased with increase in production by 105%.

Alqsair (2023) [22] focused on the numerical simulation of the surface evaporation process within a 3D solar still. Inside the solar still chamber, water is maintained at a specific level and undergoes evaporation due to solar heat. The numerical simulation utilizes computational fluid dynamics (CFD) techniques. The primary objective of this study is to enhance the performance of the solar still system by increasing the rate of surface evaporation.

Sonawane et al., (2022) [23] examines how different absorber materials influence the performance of a solar still using CFD simulation, along with economic and environmental assessments. The study compares various absorber materials based on their thermal properties and evaluates their effect on heat transfer, evaporation rate, and overall water productivity. The results indicate that materials with higher thermal conductivity significantly enhance heat absorption and distribution, leading to improved evaporation and increased distillate yield.

Ojo et al. (2022) [24] examined a single sloped basin solar still was employed for the treatment of wastewater obtained from a paint industry. The efficiency of solar distillation in the treatment of the wastewater over a period of 8 consecutive days was examined. 20 Litres of wastewater was placed inside the solar still under outdoor conditions. Approximately 5 Litres of distillate water was obtained at the end of the experiment. The quality of the untreated wastewater and its distillate were determined. In addition, solar radiation and volume of distillate obtained for each day was measured.

Dsouza and Mallikappa (2023) [25] addressed the growing need for freshwater in regions affected by water scarcity, particularly in coastal and desert areas. The focus is on evaluating the effectiveness of a solar-powered desalination system, which utilizes a single slope step type solar still and an Evacuated Tube Collector (ETC) to produce fresh drinkable water. Additionally, CFD analysis is conducted to gain insights into the natural convection of heat transfer within a glass tube, which creates a buoyant flow of saline water. The design consists of a solar evacuated tube, which heats up due to the exposure to sun rays and this heat is transferred to the impure/saline water (effluent). The water is then discharged to a single slope step type solar still which absorbs energy from sunlight and increases the evaporation rate in the solar still.

Prasad et al. (2023) [26] Potable water is a basic need in various aspects of daily life. The conversion of brackish water to potable water through conventional sources is costly and environmental issues are associated. In this regard, solar energy is a preference over fossil fuel or another energy source because of its cost and environment. Therefore, solar still is very popular, but the performance still must be improved to meet our potable water demand. In the present work, the productivity of the still is tested with various operational parameters such as glass plate inclination 27°, 28°, and 29°, and basin heat absorption capacity was also observed with sand, clay sand, and granite for water yield. Water yielding is also affected by water depth in basing investigated as 2, 3, and 4 cm for productivity.

3. RESEARCH METHODOLOGY

3.1 Design of Solar Still

A solar still is a simple device that utilizes solar energy to produce fresh water. Fig. 1 shows a single slope solar still. It is composed of a glass housing that allows smaller wavelength

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radiations (A) to enter the solar still but does not allow larger wavelength radiations to escape the glass housing, thus producing a high temperature within the solar due to the greenhouse effect. The roof of solar still, is made of glass, is tilted at a specific slope to allow the maximum possible direct solar radiations to enter the solar still. As the solar radiations fall on the glass roof of the solar still a small fraction of it is reflected out by the glass (β), a part of it is absorbed by the glass (C), while the remaining part enters the solar still. The sides of the single slope solar still are made up of glass as well. The glass sides allow the shorter wavelengths coming from direct radiations to enter the solar still.

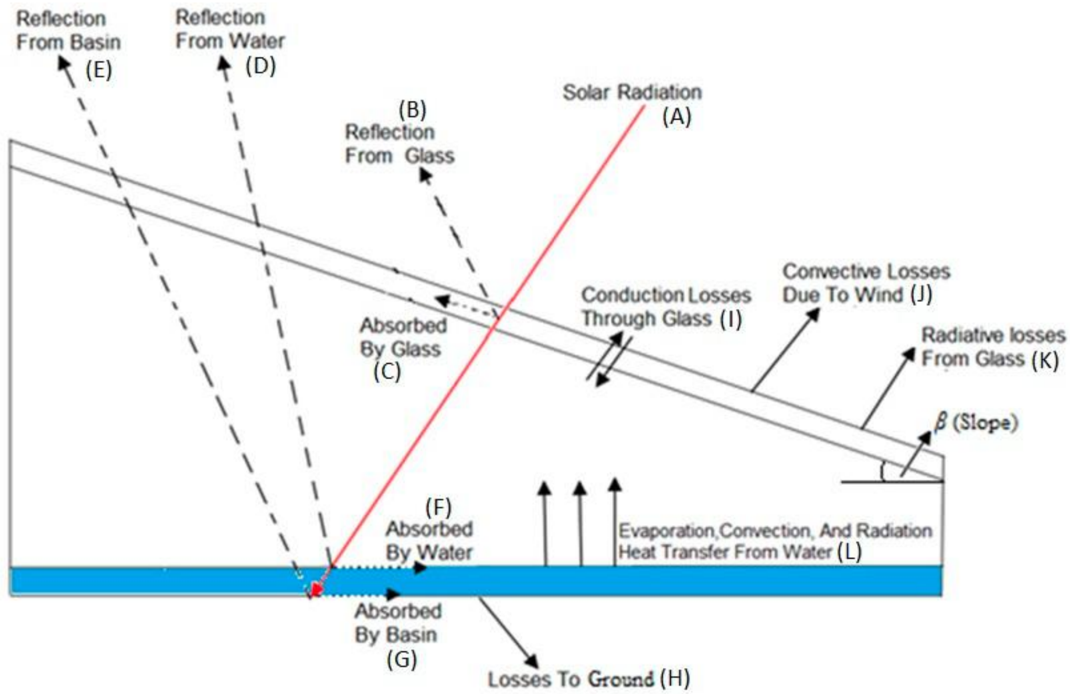

Fig. 1: Single slope solar still

If brackish water (saline water) is placed inside the basin of the solar still, a part of the solar energy will also be reflected by the brackish water (D) as well as the basin material (E). There will also be some losses of energy to the ground (H), whereas the remaining solar energy that has entered the single slope solar still will be absorbed by the brackish water (F) and the basin (G). This absorbed solar energy by the brackish water causes evaporation inside the solar still (L). The evaporated water is pure (without any contamination) and is drawn out by convection to meet the inner surface of the glass roof. Thus, the inner surface of the glass housing, being in contact with the evaporated water, is at a comparatively higher temperature. The outer surface of

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the glass housing is at a comparatively lower temperature, being in contact with outside air. Hence, the temperature gradient between the inner and outer surfaces of the glass housing allows conduction heat transfer (I), resulting in the condensation of pure water, which is then collected as fresh water. During the process, a small fraction of energy is lost by the convective losses (J) due to the wind and the radiative losses from the glass (K). The left-over brackish water inside the basin of the solar still becomes more concentrated and is later removed and replaced with new brackish water.

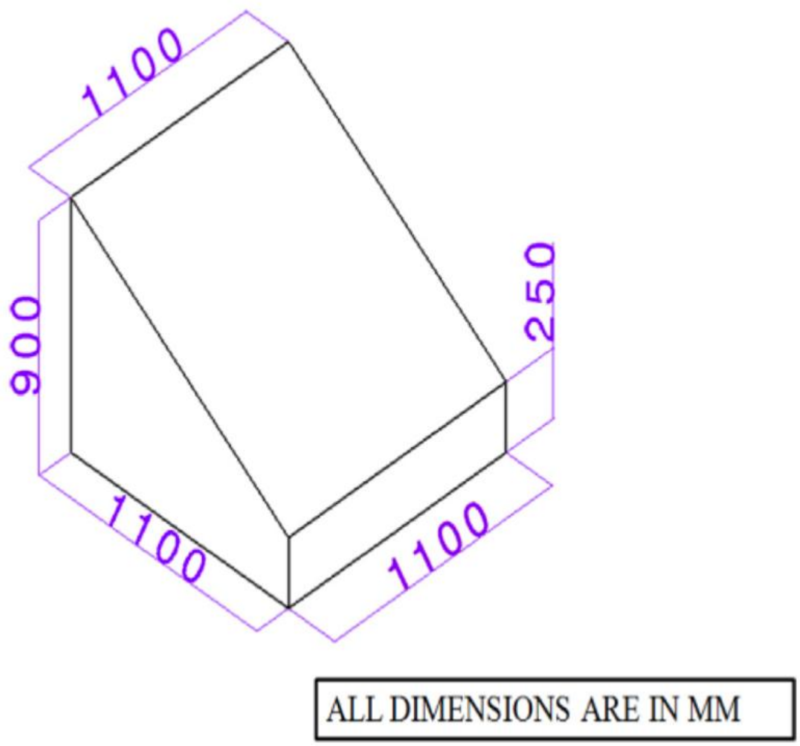

Fig. 2: Geometry of single slope solar still [23]

3.2 Parameters and Levels

The Taguchi method, developed by Genichi Taguchi, is a statistical approach to optimization that is widely used in engineering and quality control. It helps in optimizing performance and minimizing variation in manufacturing processes. When applying the Taguchi method to select parameters, such as in experimental design, the following steps are generally involved:

1. Identify the Factors (Parameters):
   Clearly define the factors (independent variables or parameters) that may influence the performance of the system or process.

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2. Determine the Levels of Each Factor:
   Specify the different levels or settings for each factor that will be tested. These levels should cover the potential range of variation for each factor.
3. Define the Experimental Design:
   Use the orthogonal array provided by Taguchi to plan the experiments efficiently. The orthogonal array helps to reduce the number of experimental runs while still capturing the main effects and interactions.
4. Select the Performance Measure (Response):
   Clearly define the performance measure or response variable that you want to optimize. This could be a measure of quality, efficiency, or any other relevant metric.
5. Conduct Experiments:
   Perform the experiments based on the designed orthogonal array. Each combination of factor levels represents a unique experimental run.
6. Collect Data:
   Record the data for each experimental run, including the performance measure or response variable.
7. Analyze Data:
   Use statistical methods to analyze the collected data. Taguchi uses signal-to-noise (S/N) ratios to evaluate the effect of each factor and the interaction between factors.
8. Identify the Optimal Parameter Settings:
   Determine the combination of factor levels that provides the optimal performance or the highest S/N ratio.
9. Conduct Confirmation Runs:
   Validate the results by conducting confirmation runs with the identified optimal parameter settings.

Based on the previous studies, glass thickness and slope have been selected as a input parameter (Ali et al., 2023). The range of slope angle has been varied from 20^o to 30^o with three levels and glass thickness was varied from 0.01 to 0.02 mm (see Table 1). These two parameters are input parameters which was varied to examine performance parameters such as mass flow rate. The three parameter with three levels as shown in Table 1 constituents nine simulation based on L9 orthogonal array. Based on Table 2, total nine models and nine simulation was done by varying slope angle and solar intensity.

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Table 1: Parameter and range

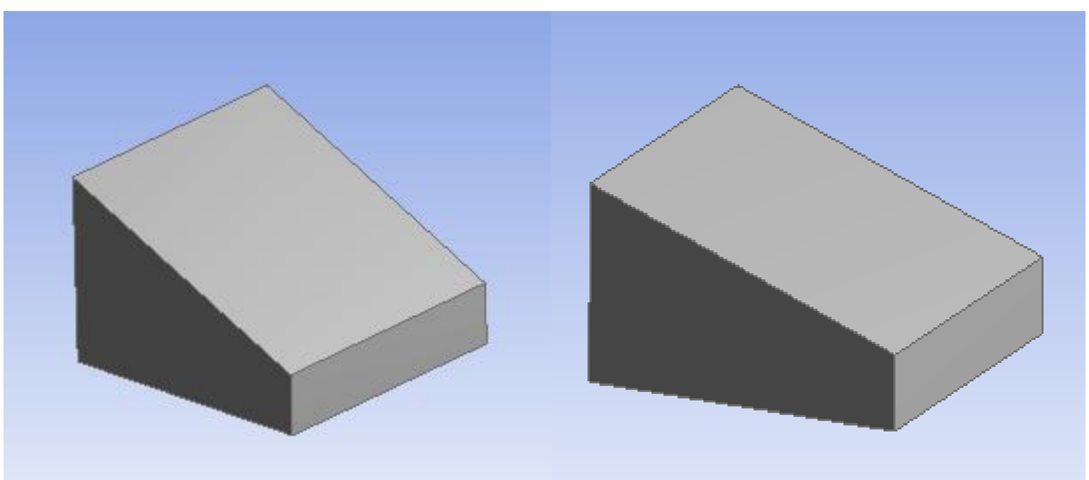
	I	II	III
Slope	20^o	25^o	30^o
Glass thickness	0.01	0.02	0.03

Table 2: L9 orthogonal array

Run	Slope	Glass thickness, m
1	20^o	0.01
2	25^o	0.02
3	30^o	0.03
4	20^o	0.02
5	25^o	0.03
6	30^o	0.02
7	20^o	0.03
8	25^o	0.01
9	30^o	0.02

3.3 CAD modelling of single slope solar still

Using ANSYS design modular, a three-dimensional CAD model showcasing a single slope solar still has been carefully crafted. The dimensions of the base measure 1.1 m x 1.1 m, while the front wall stands at 0.25 m in height and the back wall at 0.9 m. Refer to figure 4.3 for a visual representation of the three-dimensional CAD model of the solar still.



model 1 model 2

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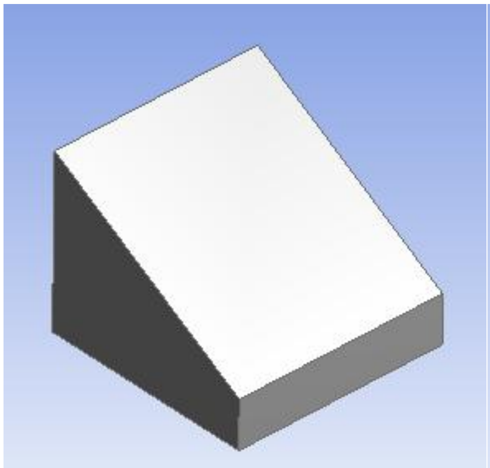
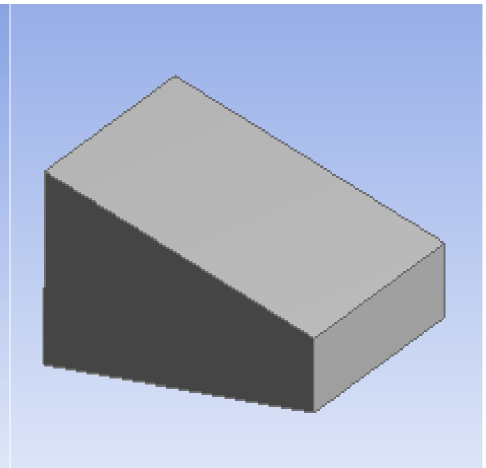
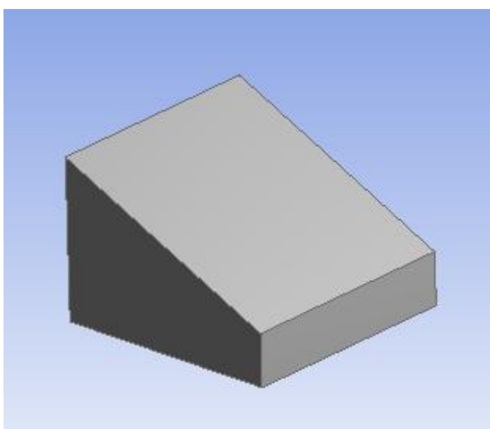


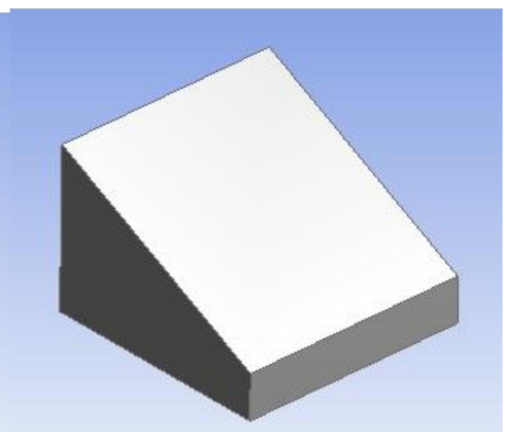
model 3



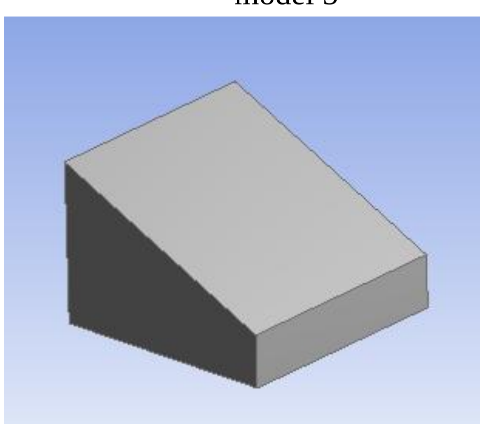
model 4



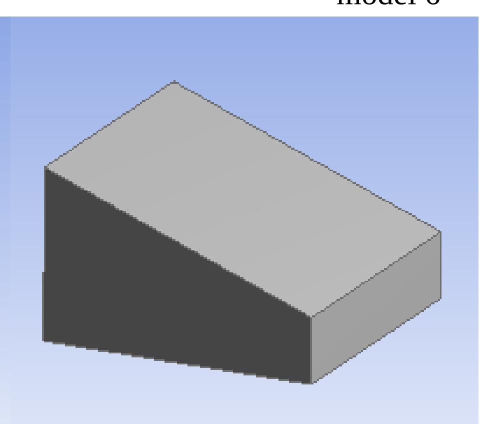
model 5



model 6



model 7



model 8

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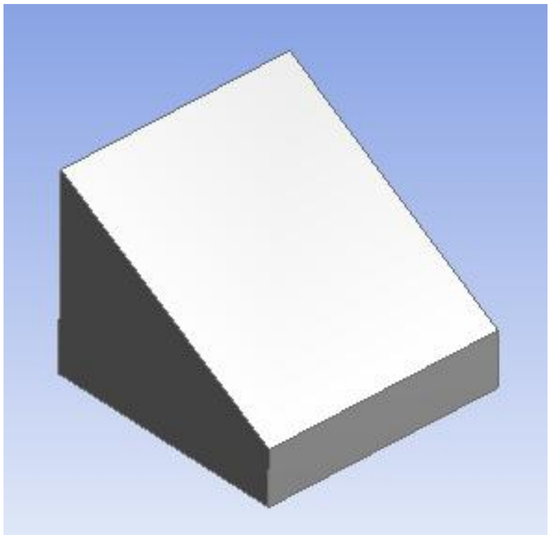

model 9

Fig. 3: Nine CAD model of single slope solar still

3.4 Meshing

Once the CAD geometry of the single slope solar still was completed, it was imported into ANSYS workbench for further analysis. The next step in this process was meshing, an essential component of finite element analysis. During this step, the CAD geometry was broken down into numerous small pieces, known as the mesh. The mesh created for the single slope solar still in this project can be seen in Figure 4.4, showcasing the intricate breakdown of the geometry for analysis. Total number of nodes: 137082 and total numbers of Elements are 128832 having hexahedral type of element.

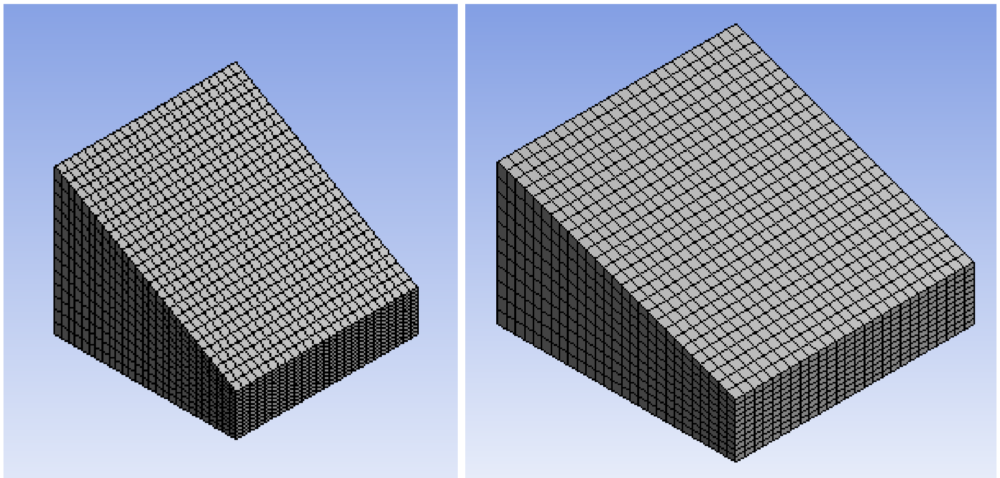

Fig. 4: Meshing of single slope solar still

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4. RESULTS AND DISCUSSION

4.1 Validation of CFD Model

The main objective of the present work is to determine the maximum output of water that is able to be produced from the single slope basin and compare their efficiency for the validation of the work on research paper of Sonawane et al [23]. The study perform computational fluid dynamics analysis by creating three-dimensional CAD model of slope solar still using ANSYS design modular having the dimensions of base 1.1 m x 1.1 m, front wall dimensions of 0.25 m in height and back wall of 0.9 m for single slope. The obtain results have been compared with published literature.

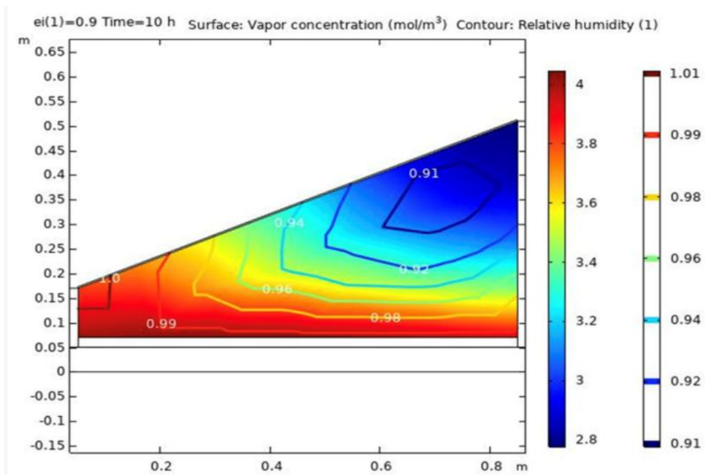

Fig. 5: Water Volume Fraction on Glass [Sonawane et al., 2022]

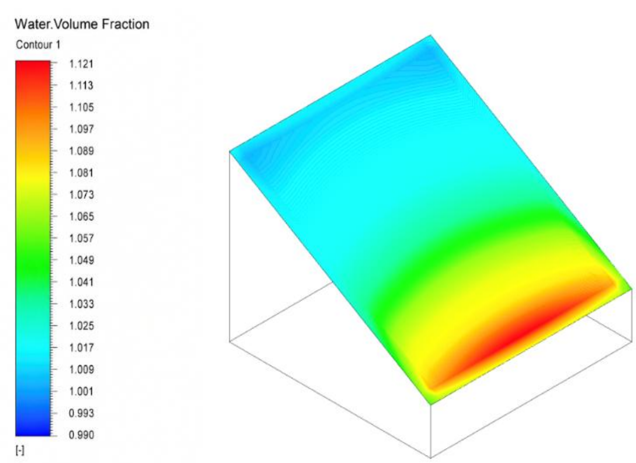

Fig. 6: Water Volume Fraction on Glass [Present study]

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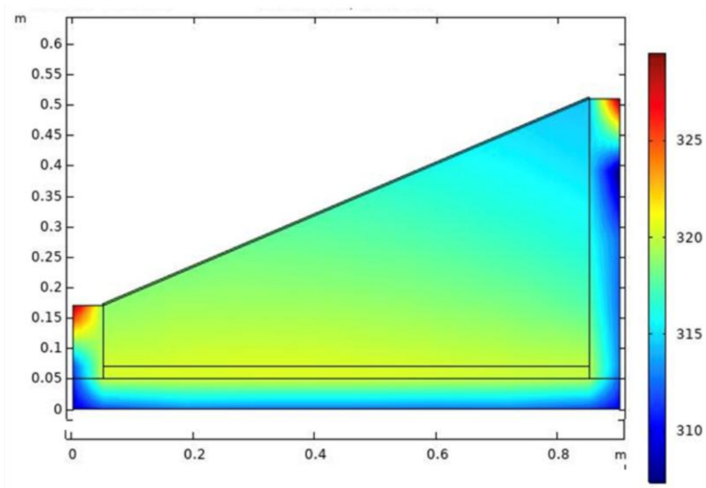

Fig. 7: Temperature on Glass [Sonawane et al., 2022]

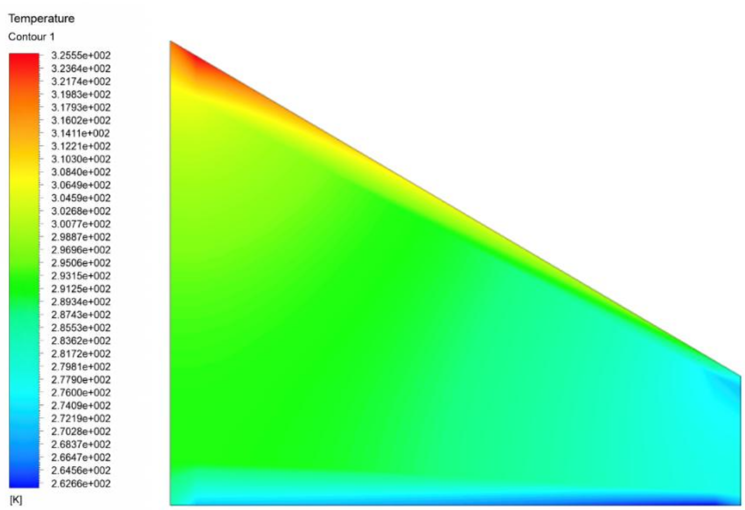

Fig. 8 Temperature on Glass [Present study]

From the above contour diagrams, it has been observed that Volume fraction of water showing 3.69% variation while the temperature difference of 6.1 degree showing 1.99% variation. All above compared results show very good agreement between base paper and present work, hence the further analysis with same boundary with modified design have to be done.

Table 3: different parameter compared with Sonawane (2022) & present work:

S. No	Parameters	Sonawane (2022)	Present work	% Difference
1	Water volume fraction on Glass	1.01	1.121	10.99
2	Temperature (K)	325	325.5	0.15

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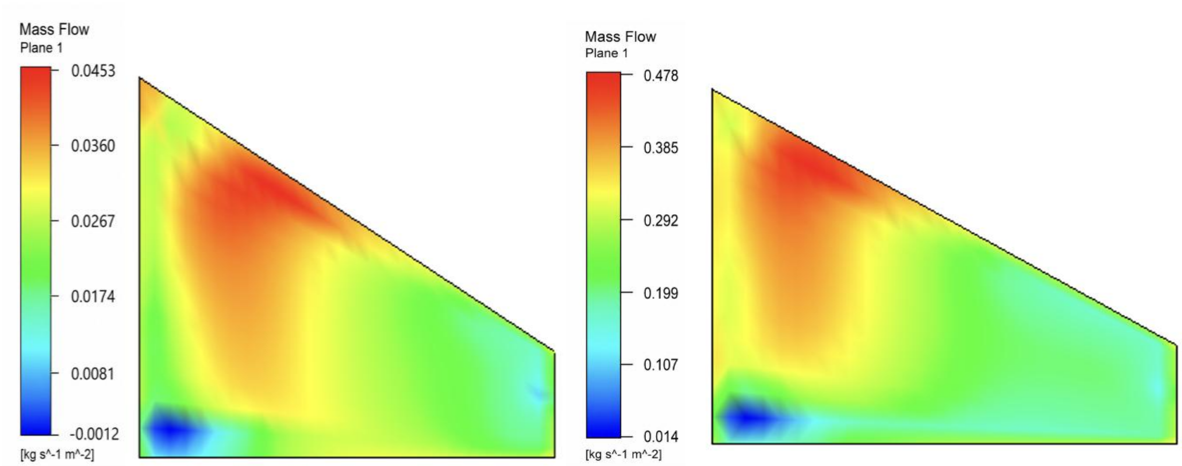
4.2 Computational fluid dynamics analysis of single slope solar still

After performing computational fluid dynamics analysis on single slope solar still for mass flow of condense liquid following contour has been observed on a section in X-Y plane and at Z = 0.55 m, the maximum value of mass flow rate of 0.0453 kg/s-m^2 as shown in figure 9a.



(a) (b)

Fig. 9: Contour result (a= slope =20^o and glass thickness=0.01m); (b=slope =25^o and glass thickness=0.02m)

After performing computational fluid dynamics analysis on single slope solar still for mass flow of condense liquid following contour has been observed on a section in X-Y plane and at Z = 0.55 m, the maximum value of mass flow rate of 0.478 kg/s-m^2 as shown in figure 9b.

4.3 Simulation Results

The objective of this analysis is to examine the influence of these parameters on the productivity of the solar still and to identify the optimal combination for maximum distillate yield. Table 4 summarizes the simulation results, highlighting the variation in productivity corresponding to different parameter combinations.

Table 4: Simulation Results-L9 orthogonal array

Run	Slope	Glass thickness, m	Mass flow rate, Kg/s-m^2	Productivity, ml/hr
1	20^o	0.01	0.0453	221.73
2	25^o	0.02	0.478	225.56
3	30^o	0.03	0.452	227.49

4	20°	0.02	0.498	265.86
5	25°	0.03	0.462	279.69
6	30°	0.02	0.465	293.52
7	20°	0.03	0.0339	271.24
8	25°	0.01	0.471	282.19
9	30°	0.02	0.482	285.32

4.4 Optimisation

The S/N ratio is used to identify the optimal parameter settings that minimize variability and enhance system performance. The analysis helps in determining the most influential factors and their respective levels for achieving improved mass flow characteristics in the solar still. Table 5 shows the response table for mass flow.

Table 5: Response Table for Signal to Noise Ratios for mass flow

Level	Slope	Glass thickness, m
1	0.1924	0.2582
2	0.4703	0.4808
3	0.4663	0.3160
Delta	0.2779	0.2226
Rank	1	2

The response table for Signal-to-Noise (S/N) ratios illustrates the influence of slope and glass thickness on the mass flow rate of the solar still. Each level value represents the average response of mass flow rate at that specific level of the parameter. It is observed that for slope, Level 2 (25°) yields the highest value, followed by Level 3 (30°), while Level 1 (20°) shows the lowest performance, indicating that an increase in slope enhances the mass flow rate up to an optimal point. Similarly, for glass thickness, Level 2 (0.02 m) provides the best performance compared to Levels 1 and 3. The Delta value, which represents the difference between the maximum and minimum responses, is higher for slope (0.2779) than for glass thickness (0.2226), indicating that slope has a greater influence on mass flow rate. This is further supported by the ranking, where slope is identified as the most significant parameter, followed by glass thickness.

Table 6: Response Table for Signal to Noise Ratios for productivity

Level	Slope	Glass thickness, m

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1	47.62	46.89
2	48.91	49.12
3	49.45	49.97
Delta	1.83	3.08
Rank	2	1

The response table for Signal-to-Noise (S/N) ratios for productivity presents the influence of slope and glass thickness on the performance of the solar still under different levels. In Taguchi analysis, the S/N ratio (larger-the-better criterion) is used to evaluate the robustness and efficiency of the system, where higher values indicate better productivity.

From the table, it is observed that for slope, the S/N ratio increases from Level 1 to Level 3, with Level 3 showing the highest value. This indicates that higher slope angles tend to improve productivity by enhancing condensation flow and heat transfer. For glass thickness, a similar increasing trend is observed, with Level 3 (0.03 m) giving the highest S/N ratio, suggesting that thicker glass within the studied range improves productivity due to better thermal retention and reduced heat loss.

The Delta values represent the difference between the maximum and minimum S/N ratios for each parameter. Glass thickness shows a higher Delta value compared to slope, indicating that it has a greater influence on productivity variation. The ranking further confirms this observation, where glass thickness is ranked 1 (most influential factor), followed by slope ranked 2.

The optimum parameter settings are obtained using the Signal-to-Noise (S/N) ratio approach by selecting the level of each factor that yields the highest S/N value. For mass flow rate, the optimal levels are found to be slope at 25° and glass thickness of 0.02 m, whereas for productivity, the optimal combination is slope at 30° and glass thickness of 0.03 m. Since productivity is considered the final performance indicator, the optimal configuration of the solar still is identified as a slope of 30° with a glass thickness of 0.03 m. The corresponding temperature values are obtained from the simulation results at this optimal configuration, as temperature is treated as a response variable rather than a control factor in the Taguchi design.

4.5 Results Confirmation

Table 7: Parameter determination and comparison

Parameter	Conventional Solar Still	Optimized Solar Still
Slope (°)	20°	30°
Glass thickness (m)	0.01 m	0.03 m
Mass flow rate (kg/s·m²)	0.0339	0.498

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Productivity (ml/hr)	221.73	293.52
Temperature (K)	325.0	325.5

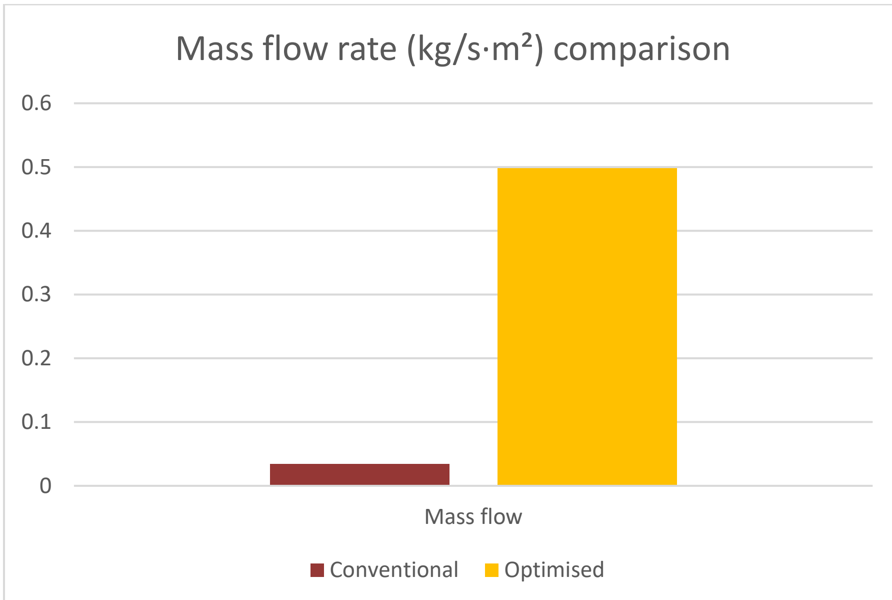

Fig. 10: Mass flow rate comparison

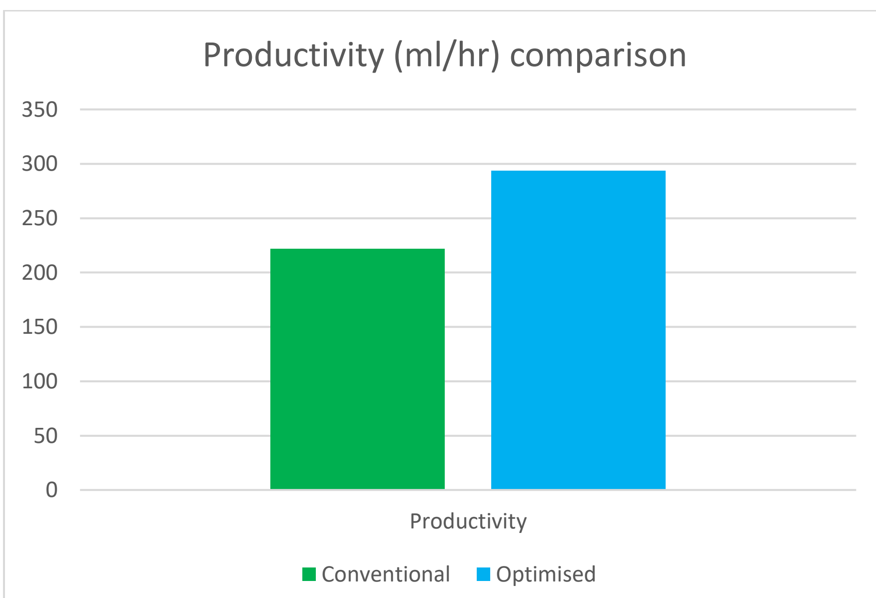

Fig. 11: Productivity comparison

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Table 10 and 11 presents a comparison between the conventional and optimized solar still in terms of key performance parameters. The optimized solar still shows significant improvement in all considered aspects due to the modification of design and operating conditions. In the optimized configuration, the slope is increased from 20° to 30°, and the glass thickness is enhanced from 0.01 m to 0.03 m, which contributes to improved heat transfer and condensation behavior. As a result, the mass flow rate increases substantially from 0.0339 kg/s·m² in the conventional system to 0.498 kg/s·m² in the optimized design. Similarly, productivity is enhanced from 221.73 ml/hr to 293.52 ml/hr, indicating a considerable improvement in distillate output. The temperature also shows a slight increase from 325 K to 325.5 K, which supports higher evaporation rates. Overall, the comparison clearly demonstrates that the optimized solar still performs more efficiently than the conventional design due to improved thermal and geometrical parameters.

5. CONCLUSION

The CFD assessment involved the creation of three-dimensional CAD models for single slope solar still using ANSYS Design Modular software. The single slope solar still had a base dimension of 1.1 m x 1.1 m, with a front wall height of 0.25 m and a back wall height of 0.9 m. The assessment utilized a Multiphase model employing a Volume of Fluid (VOF) implicit formulation, incorporating three Eulerian phases: air, liquid water, and water vapor. Multi-phase interactions, including evaporation-condensation for mass transfer mechanisms from vapor to vapor and vapor to water, were considered. For meteorological accuracy, solar radiation was applied to the transparent cover of the solar stills. The geographical location used for this assessment was longitude 77.40E, latitude 23.25990N, with a time zone of GMT +5:30 hours in Bhopal.

- This study investigated the performance enhancement of a single-slope solar still through variation and optimization of key geometrical and operating parameters. Computational and Taguchi-based analyses were employed to evaluate the effects of slope angle, glass thickness, mass flow rate, and productivity under different configurations. The results clearly indicate that both slope and glass thickness significantly influence the thermal behavior and overall efficiency of the solar still, with slope showing a stronger effect on mass flow rate and glass thickness playing a dominant role in productivity improvement.
- The optimized configuration, identified as a slope of 30° and a glass thickness of 0.03 m, demonstrated superior performance compared to the conventional design. Under optimized conditions, substantial improvements were observed in mass flow rate and distillate yield, along with a slight increase in basin temperature, which collectively enhanced evaporation and condensation processes. The productivity increased notably

from 221.73 ml/hr to 293.52 ml/hr, confirming the effectiveness of the proposed modifications.

- Overall, the study concludes that appropriate optimization of design parameters can significantly improve the performance of solar stills without increasing system complexity. The results also highlight the potential of solar stills as a sustainable and low-cost solution for freshwater production, particularly in regions with high solar availability.

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