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Evaluation of Distillate Yield in 3D-Single Slope Basin Type Solar Still: A Comparative Study of CFD and Experimental Approaches

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ABSTRACT

There are various merits of modelling the problem domain numerically, which include cost reduction, ease in variable control, enhanced yield, etc. These merits are known to everyone. This work provides a one-of-a-kind and complete evaluation of distillate yield i.e. productivity in a single slope solar still by combining computational fluid dynamics (CFD) models with experimental data. Unlike earlier research, which frequently focuses on either simulation or experimental data in isolation, this study presents a direct comparison of the two methodologies, showing their distinct strengths and limitations. The experimental model of solar still was fabricated for experimental study. Based on the experiment, distillate yield was observed every hour of the day. The experiment was conducted on the roof of Balaju School of Engineering and Technology, Kathmandu. On the other hand, CFD model was based on the practical model used for experimentation. Most of the variables were chosen as per the physical domain, such as the material of the solar still and the angle of inclination. From the comparative study, it was found that distillate yield resulted from simulation through CFD analysis, and the experiment followed a similar trend. There was an error of about 26%, which might be the result of losses that occur in practical applications that were not considered during CFD analysis. From the research, it was found that, ANSYS is a powerful tool for performing CFD analysis of practical problems involving fluid flow. Thus, it can be used for modelling and simulating more complex problems in the future.

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1. Introduction

One of the most critical issues of global interest in the world's current situation is the need to reach pure and clean water for drinking around people in urban and rural areas. Water availability amongst the people shows the living standard and socio-economic aspect of any society. Water is, therefore, one of the people's basic needs in addition to food and air [1].

In the present context, green technology is emerging due to its ability to produce zero emissions. There are many distillation methods through which water available could be processed to make it clean and drinkable. However, these methods, such as reverse osmosis (RO), etc., are power intensive, making them not feasible to use in rural areas as there is a lack of electricity. Thus, solar still may be a viable option for achieving a cost-effective and clean solar desalination process. [2]. Solar still is a static device made up of proper insulating and absorbing material with glass imposed over it. It requires solar energy and could be fabricated with minimal and readily available material. The evaporation of water inside the solar still and condensation of the vapour inside the solar still are the mechanisms on which it is based [3]. Heavy salts are left behind, and lighter vapour goes up due to evaporation and gets collected in the collector after condensing in the glass due to gravity [4].

This method of desalination by applying solar still using glass and rectangular box is traditional and old to obtain clean drinking water from saline water [5]. This method could be the potential solution for the availability of clean drinking water to the people of rural areas due to its simplicity, ease, cleanness and lack of pollution. However, this device's major drawback is that the distilled water output is very low. Various parameters, such as operational, design and climatic parameters, impact the solar still's performance [6]. This drawback could be overcome if the parameters responsible for distillate output could be optimized. The essential parameters evaluated were solar radiation, a tilt angle of the glass, depth of saline water, and blackened substance. Thus, the experiment and CFD analysis were done for the solar still having a single slope to identify significant parameters and optimize it. The details of the experiment and simulation are given in [7].

Performing experiments and comparing the results obtained with the simulation results can help design more precise and accurate solar stills, resulting in a massive improvement in the distillate yield of solar stills. CFD analysis is a tool that helps analyze the physical problem by transforming it into a virtual model. This consumes less time than the time consumed during the experiment. Apart from this, CFD used less physical effort [8]. Therefore, if this comparison is in good agreement, further modification and improvement in designs and iterations could be done through CFD only. Finally, the best result in the iterations could be used for prototyping. Thus, the present paper aims to compare the experiment and CFD analysis of single-slope solar stills. The excellent agreement between the experimental results and the results obtained from the computational analysis will be helpful for future study and parameter optimization [8,10,11].

Thus, this study presents a unique and comprehensive evaluation of distillate yield in a single slope solar still by integrating Computational Fluid Dynamics (CFD) simulations with experimental results. Unlike previous research that often focuses on either simulation or experimental data in isolation, this work provides a direct comparison between the two approaches. The novelty lies in the development of a more accurate predictive model by leveraging the insights gained from both methodologies, thus enhancing the understanding of heat and mass transfer processes within the solar still more precisely and accurately. Additionally, the study introduces a more reliable and optimized design framework for future solar still applications by the application of CFD with the optimization of various performance parameters.

2. Methods and Equations

The solar still consisting of a single slope along with its significant parts is shown in ***Figure 1.*** The reader is referred to [7, 9] for the detailed solar still design. The hourly production of distilled water output, i.e. distillate yield, is given as:

$$m_{ew} = \frac{Q_{Ewg}}{L_{ev}} \quad (1)$$

Similarly, one day distillate yield is given by the summation of hourly production of distillate yield i.e. ***Eq. (1)*** as:

$$\mathbf{M_{ew}} = \sum_{i=1}^{24} \mathbf{m_{ew}} \quad (2)$$

And, Evaporative heat transfer between water and inner glass as:

$$\mathbf{Q_{Ewg}} = \mathbf{h_{Ewg}} \times (\mathbf{T_w} - \mathbf{T_g}) \quad (3)$$

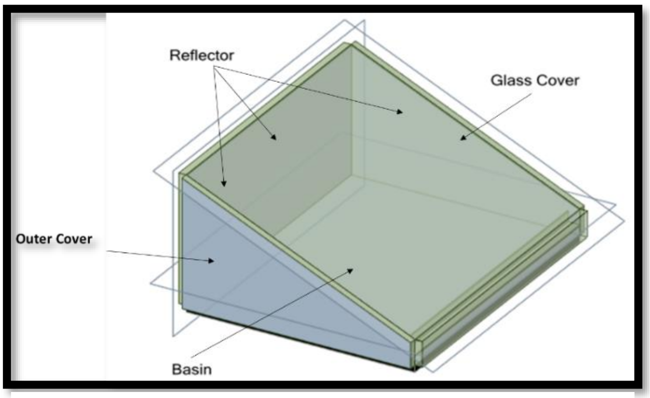

Figure 1. *Components of solar still [7]*

Where,

Evaporative heat transfer coefficient of glass: $h_{Ewgi} = 16.28 \times 10^{-3} \times h_{Cwgi}\left(\frac{(P_w - P_g)}{(T_w + T_g)}\right)$

Partial Pressure of Water inside basin: $P_w = \exp\left(25.317 - \frac{5144}{T_w + 273}\right)$

Partial Pressure of condensing glass: $P_g = \exp\left(25.317 - \frac{5144}{T_g + 273}\right)$

Convective heat transfer coefficient of class: $h_{Cwgi} = \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268900 - P_w}\right]^{1/3}$

L_{ev} = latent heat of evaporation

The main parameters on which productivity depends, as per the above expression, are the water temperature and the glass temperature. The temperature of water and the temperature of glass affect productivity. The temperature of the water and glass depends on several variables, including the volume of water in the basin, tilt angle, insulation type, thickness of the glass, and type of material used for the basin. The simulation and experiment results are compared in light of [7].

3. Experimental Setup

The experimental setup was fabricated with its major components, as shown in ***Figure 1***. The fabrication of the solar still was done at the mechanical workshop of Balaju School of Engineering and Technology, Kathmandu. The size and dimension of solar still was calculated as follows with the help of schematic diagram shown in ***Figure 2***.

Using simple trigonometry,

$$H = Y + S$$

$$H=Y+L\tan\beta$$

For condensing glass cover:

$$\cos\beta=L/Z$$

$$Z=L/\cos\beta$$

Basin area:

$$A=L\times B$$

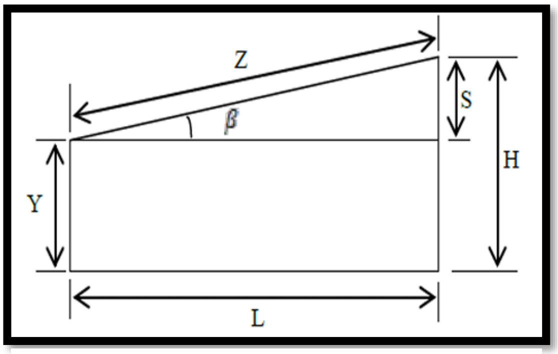

Figure 2. *Schematic diagram of solar still*

The major components of solar still for fabrication work was basin, glass cover, distilled water collector, internal reflectors and input water. The criteria for selection of various component is shown in ***Table 1***.

Table 1*. Component, material and their properties*

Component		Material	Properties
1.	Transparent Surface	Glass	Low water absorptance, high thermal conductivity, withstand effect of weather, wind, sunshine, dust, etc.
2.	Absorber (Basin)	Galvanised Iron (GI) Sheet	Minimum corrosion, high thermal conductivity and reflectivity, low cost and easily available
3.	Reflector	Aluminium foil	High radiation absorptivity, corrosion stability, high thermal conductivity, low cost
4.	Casing or Cover	Plywood	Uniform strength and durable, light weight, insulation
5.	Insulation	Glass Wool	Very good insulation
6.	Sealant	Araldite	Withstand high temperature, organic liquid resistance, difficult to break, cheap and easily available
7.	Drain Pipe	PVC	Stable to corrosion, not poisonous to water, low cost and availability
8.	Collection Trough	Stainless Steel	Stable to corrosion, not poisonous to water

At the latitude angle of Kathmandu, the inclination angle of condensing glass was considered. A 5 mm thick condensing glass was employed. The dimensions of the solar still were determined to be 1 m x 0.8 m. The two-walled body of the solar still was fabricated. The inner wall was made of GI sheet, and the outer wall was composed of plywood, between which insulating material, i.e., glass wool, was attached. Insulation was provided to minimize the loss of heat during the experiment. The inner absorber area of the solar still, which absorbs heat, was painted black to maximize the absorptivity.

Similarly, aluminium foil was placed on the inner wall to concentrate the solar irradiance towards the basin area for maximum heat. This experiment was carried out on the roof of Balaju School of Engineering and Technology, Kathmandu. Various steps of fabrication involved welding of support structure, plyboard cutting as per required size, GI sheet folding by properly cutting as per the required dimension, painting the base of GI sheet, assembling of insulating material along with inner sheet and outer plyboard and finally placement of transparent condensing glass on the top as per the given slope. Leakage was also checked during the experimentation process.

Thermocouples and a digital multimeter were used during the data collection while experimenting. The k-type thermocouple was employed to take readings of water or basin temperature and the temperature of condensing glass during the process. ***Figure 3*** shows the experimental setup of the solar still after fabrication. Similarly, the thermocouple reading was read from the Digital Multimeter Mars DMM-90. The Department of Hydrology and Meteorology, Kathmandu, also provided the necessary data on hourly radiation from the sun in Kathmandu Valley. The experiment took place from 7:00 AM morning till 6:00 PM evening. The water and glass temperature data, along with distillate yield, was noted hourly [9].

Figure 3. *Experimental setup of solar still*

Following steps were taken for performing the experiment:

Step 1: Solar still was cleaned and any water present in basin was drained out.

Step 2: Working condition of each and every components of the device were checked.

Step 3: One thermocouple was dip inside the water in basin and another thermocouple was placed on the glass cover for the reading of basin and glass temperature.

Step 4: Bothe the thermocouples were connected to the digital multimeter in order to get the temperature data.

Step 5: Measuring cup was used for obtaining the data of hourly distillate yield.

Step 6: Sealing of outer cover of solar still with glass was done with the help of U-rubber.

Step 7: Data obtained for temperature of glass and basin along with hourly volume of water inside the measuring cup was noted hourly.

Step 8: These steps were repeated at the day on which experiment was performed.

4. CFD Modelling and Simulation

Initially, the modelling was done as per the geometric dimension of the physical model. After modelling, meshing was done as shown in ***Figure 4***. Different types of mesh were examined, based upon which the final mesh structure consisted of 114345 hexahedral mesh elements with 123240 nodes. Since water plays a major role in the working principle of solar still. FLUENT (Fluid Flow) module of ANSYS was used for CFD modelling of solar still with a single slope, which employs the finite volume method (FVM) for simulation of fluid-related problems.

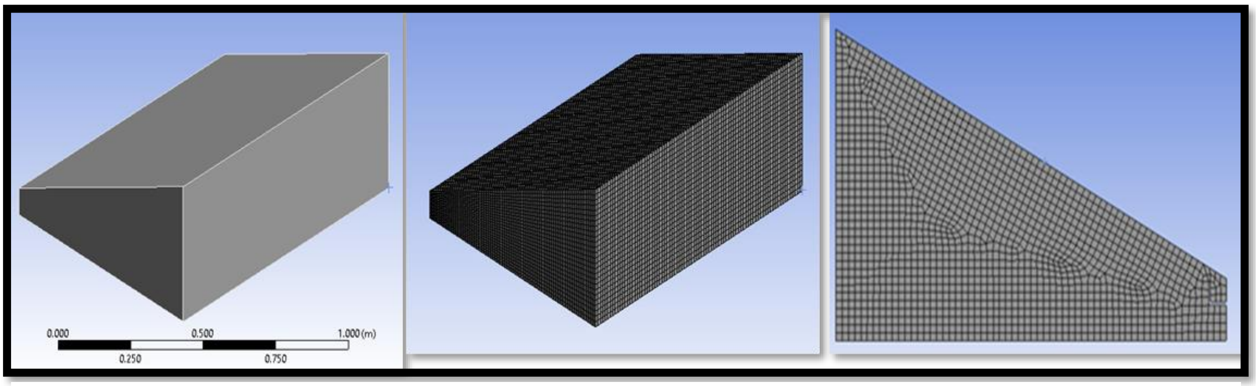

Figure 4. *Modelling and meshing of solar still*

Since the working of single slope solar still is based on the mechanism of evaporation and condensation, the presented research focuses on the simulation of condensation and evaporation phenomenon with the help of the FLUENT module in ANSYS. In the present case, the wall of the solar still is assumed to be adiabatic; various physical and thermal properties are assumed constant, glass and water temperature was considered homogeneous and free convection was assumed. Similarly, the velocity at the inlet is considered negligible, along with zero losses [10]. The law of energy, mass and momentum conservations gives the functional relationship in the CFD analysis between different variables. These were in the form of PDE (Partial Differential Equations) [11].

The present study involved multiphase, energy, viscous and radiation models during the analysis. The mixture model was chosen during multiphase modelling as mixture model due to its simplicity and less time-consuming behaviors, along with the ability to perform evaporation and condensation mechanisms in the closed system. Since there is involvement of an energy balance equation inside the solar still, the energy model was chosen after the multiphase model. For turbulent behavior, the viscous model was chosen. In the viscous model, the k-epsilon model with a standard model giving near-wall treatment as standard wall functions was selected during modelling. Finally, the radiation model was considered by taking into account the latitude and longitude values, solar loading, and solar ray tracing for the current study. The detail of input solver and solution parameters used in ANSYS FLUENT for simulation of solar still is shown in ***Table 2***.

Material with their specific properties was selected. The materials were GI sheet, Air and Glass. Then, the boundary condition was specified with proper description and thickness. Glass was taken at 0.005 m, and the absorber and adiabatic wall were at 0.025 m. The solver used implicit and explicit solutions for solving the problems. In the current modelling, the first order, the upwind method, was used for the generation of the solution since it consumes less time.

Table 2. *Input Solver and Solution Parameters Used*

Input Solver Parameters in ANSYS FLUENT		
1.	Solver	• Space: 3D space • Time: Transient condition, 1st order, implicit function • Viscous model: k-epsilon (2 equation) with standard wall function • Multiphasephase model: Mixture model • Radiation model: Rosseland model with solar tracking system and solar loading as per the data of Kathmandu, Nepal.
2.	Materials Used	• Solid: GI sheets, Aluminium and Glass • Fluid: Air, Water-liquid and Water-vapor
3.	Phases	• Number of phases: 3 • Phases: air, water-liquid and water-vapor • Primary phase: air • Secondary phase: water-liquid and water-vapor
4.	Cell zone	• Source term- Energy source
5.	Operation conditions	• Gravity axis: Y-direction • Gravity value: 9.81 m/s^2 • Operating pressure and temperature: 1.01 bar and 288.16K
Solution Method and Controls Parameters in ANSYS FLUENT		
1.	Pressure-velocity coupling	• Simple
2.	Spatial Discretization	• Pressure: PRESTO • Momentum, Energy, Liquid Volume Fraction: 1st order upwind
3.	Solution Controls	• Governing equations: Momentum, Continuity, Energy, Std. Initialization Method

Finally, the solution was initialized with a proper number of iterations based on the availability of time. After that, the result was analyzed in the form of contours and graphs [7]. The contour of temperature profile of solar still obtained during simulation is shown in ***Figure 5***. Other contours and graph can be referred to [7].

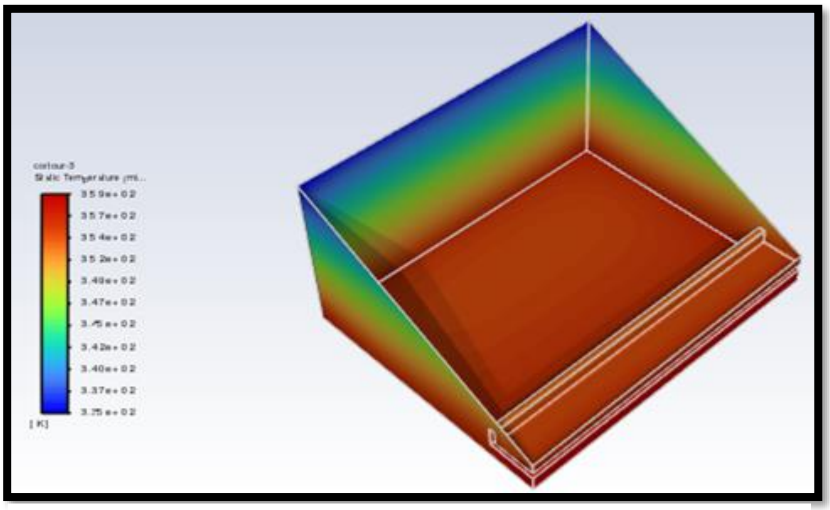

Figure 5. *Contour of temperature profile of solar still*

5. Results and Discussions

The effect of temperature of glass and temperature of water inside the basin on the productivity was tested for a set of operating conditions in experiment as well as during simulation. The comparison of the experimental results and CFD results can be done with the help of the graph plotted from the data obtained during the experiment and from the simulation. The comparison is shown with the help of graph. The comparison of water temperature, glass temperature and overall cumulative productivity is made with the help of graph.

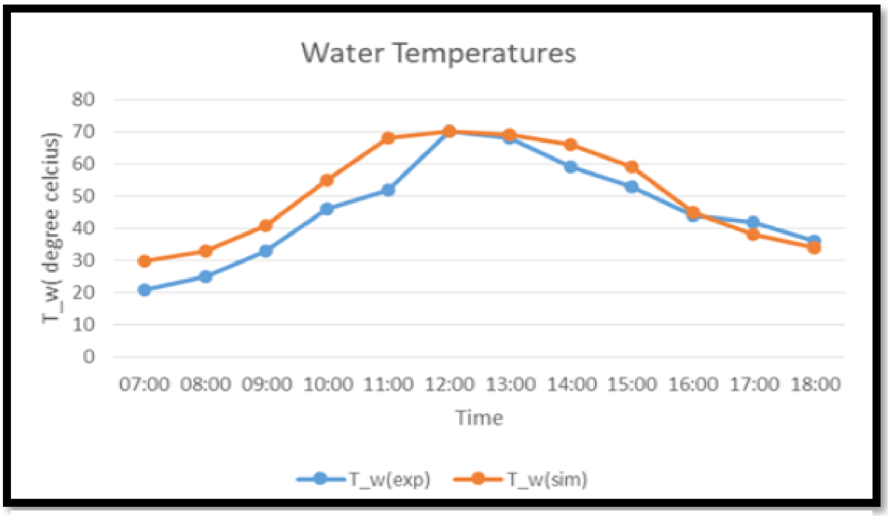

Figure 6. *Water temperature results obtained from experiment and simulation*

The graph plotted between time as x-axis and temperature of water inside basin (Tw) shows that the experimental result and simulation result follow similar trend in most of the time with very little variation as shown in ***Figure 6***. Apart from this, simulation result almost coincide with experimental result at the time when solar irradiation is at its peak i.e. at 12:00 and 13:00. At evening time, the simulation result is lower than the experiment result. There are some variation in the results of experimental analysis and CFD analysis because during simulation assumptions have been made considering ideal condition, constant thermophysical properties and negligible losses.

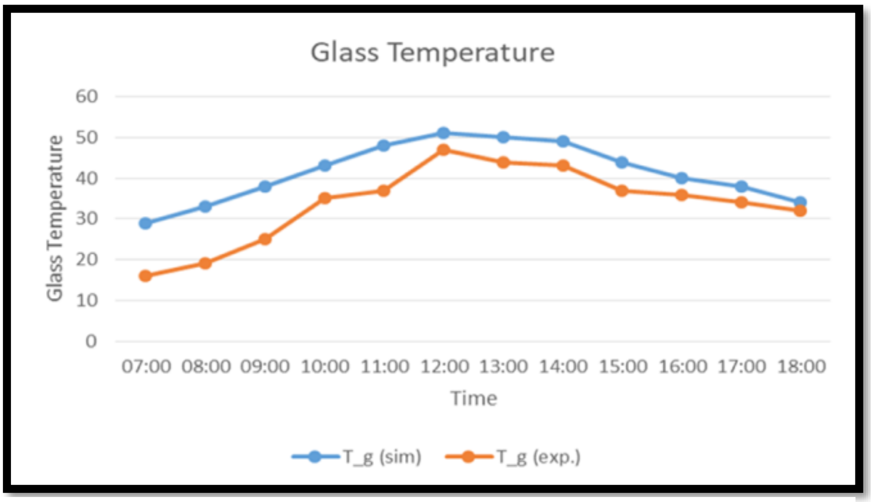

Figure 7: *Glass temperature results obtained from experiment and simulation*

Similarly, the result obtained from experimental analysis and CFD analysis of glass temperature could also be studied with the help of the graph as shown in ***Figure 7***. The graph was plotted against time of the day in x- axis and temperature of glass in y-axis. Glass temperature obtained from both experiment and simulation are in good agreement with each other as they follow similar trend but with some variation in the value. The variation in this case is also due the fact the simulation is carried out under ideal conditions considered constant thermophysical properties and assuming no losses. But in real scenario, there exists losses and the condition are not ideal due to which there is some variation in the value of both the results. Thus, experimental and simulated results of both water and glass temperature seems to be following the similar trend with some variation. These variation or differences are the cause of CFD simulation not considering cent percent practical condition. Also, it might be due to the heat losses and other losses which might occur during experimentation. The graph of glass temperature and water temperature seems to follow the pattern of solar radiation. Thus, we can say that the increase in radiation causes increase in both glass and water temperature.

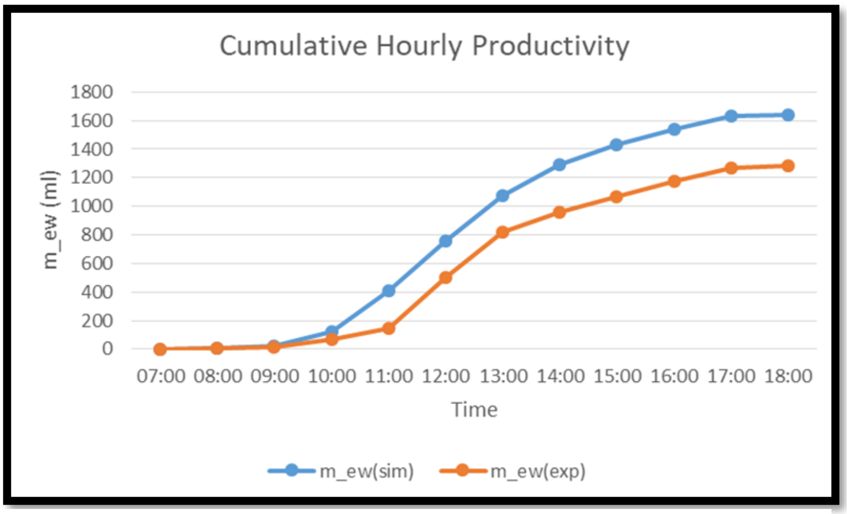

Figure 8: *Experimental productivity vs simulation productivity in solar still*

Likewise, it can be observed from ***Figure 8*** that the trend line of cumulative hourly productivity obtained from simulation follows same trend as that of the cumulative hourly productivity obtained from experiments. There is some difference in the distillate output which might be the reason of losses occurring during experiments. Other reason is same that CFD analysis considers ideal condition with constant thermophysical properties. The total productivity of the day was obtained to be 1300 ml from experiment and 1620 ml from simulation in CFD analysis. There seems to be the error of 26% between the results obtained from experiment and simulation performed during CFD analysis.

6. Conclusions

This paper's main aim was to compare the results obtained from experiment and simulation during CFD analysis of the 3D-single slope solar still. Initially, an experiment was conducted, and an experimental setup for the solar was still fabricated. After fabrication, the experiment was performed, and the required data was noted for the whole day. Results were obtained based on the data obtained. On the other hand, solar still was modelled and simulated as per the experimental setup of solar still in order to get the correct data. The simulation data, when compared with the experimental data, showed that both the results are in good agreement with some errors of about 26%. The error was due to the assumptions of ideal conditions along with the losses of heat that occur during the experiment and are neglected during simulation. Overall, the CFD model shows potential as a tool for optimizing and developing solar stills; however, more development and validation against a larger range of experimental data is required. Improvements to the model, such as more precise material attributes, better boundary conditions, and more comprehensive meshing procedures, might improve forecasts' accuracy. Future research should strive on closing these gaps so that CFD models can consistently replace or enhance experimental techniques in the development of efficient solar still designs.

The comparative study will help get more accurate future results and reduce errors to the minimum. More precise modelling and simulation could be conducted by considering different condensing glass and basin materials. Similarly, simulation and experimentation could also be performed using varying insulation materials and thicknesses. Other than this, the experiment and simulation could also be performed by considering a more precise heat transfer model in ANSYS FLUENT. Last but not least, simulation and experiment could also be performed by varying the shape of the solar still. These changes in future might result in more precise and accurate results, leading to the optimization of operational parameters that will directly improve the distillate yield in solar still.

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