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ORIGINAL CONTRIBUTION

Experimental Investigation and Performance Analysis of Double-Basin Solar Still Using CFD Techniques

Anand R. Nadgire[1] · **Shivprakash B. Barve**[1] · **Prachi K. Ithape**[1]

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Abstract Even though water is a renewable resource, most of the water present on the earth's surface is not suitable for direct human consumption. Besides, due to increasing population, urbanization, environmental pollution and growth of industries, the requirement for pure water is found increasing day by day. Also, natural resources of water can meet freshwater demand to only to a limited extent. Hence, there is a need to find a way to purify saline water with the help of an effective water desalination technique. Solar still is one such method which makes use of naturally available sunlight to purify impure/saline water. In this paper, a double-effect passive solar still is designed for experimental investigations to determine the freshwater collected at the output channel. Also, a two-phase, three-dimensional model of the unit is developed in ANSYS FLUENT for the transient state to simulate various temperatures inside the solar still and to estimate the production rate of distilled water produced. The simulation was run for 8 h, and the results have been compared with the experiment performed. Experimental investigations show a total distilled output of 3.2 L/m^2 collected in channel, whereas according to analysis results, 3.74 L/m^2 output is observed. Here, simulation results follow the similar trend as the experimental results and show good agreement with each other.

Keywords ANSYS FLUENT · Distilled water output · Heat transfer coefficient · Multi-phase · Productivity · Temperature contours

Introduction

Water, one of the most precious gifts from nature, is available in abundance for all life forms. Over 71% of the surface of the earth is covered by water, out of which only 1% of total water is useful for plants, animals and human beings for direct consumption. This small fraction of freshwater is inadequate to support the ever-increasing water demands. Hence, water desalination proves to be the best technique to assist this ever-increasing demand for potable water. Desalination is a process in which various forms of input energy as fossil fuels, solar energy or electricity is used to separate saline water into two parts, one which contains low-concentration dissolved salts that are suitable for drinking, and the other part that contains high-concentration dissolved salts which remain collected at the bottom of the basin.

There are two different methods in which water desalination may be classified, namely thermal phase change and membrane process. Thermal phase change process works on the principle of evaporation and condensation of water. On the other hand, membrane desalination makes use of a permeable membrane which acts as a micro-filter treatment and helps in desalination. Solar still is a device that follows thermal phase change process and works on the principle of solar desalination, i.e. evaporation and condensation phenomenon using naturally available solar energy and providing pure water for human beings for drinking. Solar radiations are used to heat the water to increase its temperature up to saturation temperature so that it gets evaporated to produce vapours. The vapours then start rising towards the titled glass cover, leaving behind salts in the basin and get condensed as the temperature drops below saturation temperature. The pure condensate rolls down due to gravity through the inclined

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✉ Shivprakash B. Barve
sbbarve@gmail.com

[1] MIT College of Engineering Pune, Pune, Maharashtra, India

glass, and pure water is collected in the output channel for direct use. Figure 1 shows the schematic of a simple solar still and its working principle.

The output of a solar distillation unit is measured as per day productivity per square metre area and can be improved by utilizing its latent heat of condensation. Hence, multi-effect solar stills have an additional advantage over conventional stills as in these units, latent heat of condensation released by the lower glass is reused to produce freshwater in the upper basin. This heat of condensation provides an extra source of energy to the water instead of being lost to the atmosphere. Hence, it can be said that lower basin acts as a waste heat recovery system, thereby increasing the productivity of solar still unit. Figure 2 shows the schematic of double-effect solar still.

Calculation of Hourly Distillate Output of Double-Effect Unit

The hourly output of a double-basin still can be calculated using the following relations. All the initial values of water and glass temperatures are assumed as ambient temperature [2]. The parameters used in equations are calculated using formulae from references [2, 3]. Here, $Q_{e,w-g}$ is the evaporative heat transfer rate from water to glass.

$$m_e = \Delta T \times \left(Q_{e,w-g}\right)/h_{fg} \quad (1)$$

$$Q_{e,w-g} = Q_{e,w-g,l} + Q_{e,w-g-u} \quad (2)$$

where

$$Q_{e,w-g,l} = h_{e,w-g,l} \times \left(T_w - T_g\right)_l \times A_w \quad (3)$$

$$Q_{e,w-g,u} = h_{e,w-g,u} \times \left(T_w - T_g\right)_u \times A_w \quad (4)$$

Therefore, per day production of double-effect solar still is given by

$$M_e = \Sigma_9^{17} m_e \quad (5)$$

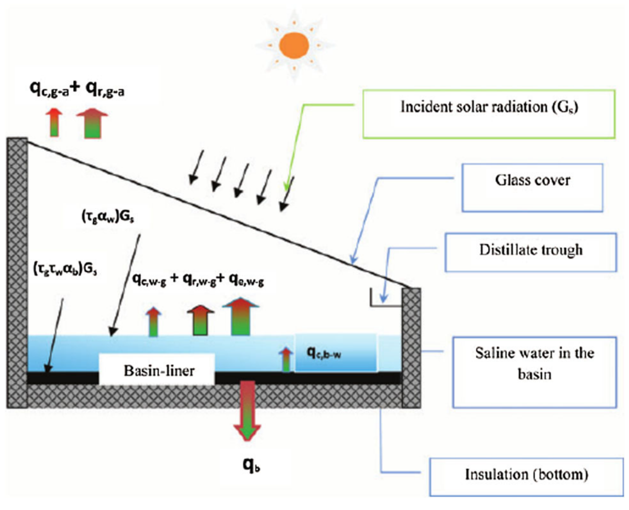


Fig. 1 Schematic of simple solar still and its working

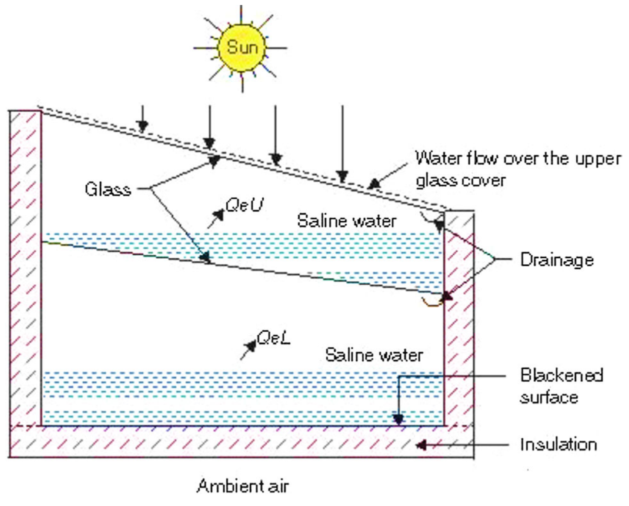


Fig. 2 Schematic of double-effect solar still [1]

Literature Review

Joe Patrick Gnanaraj et al. [2] optimized the double-basin solar still performance by use of external sources such as a mini solar pond, reflectors and FPCs. The production rate of conventional solar still, double-effect solar still with no modifications and double-basin solar still with external sources was measured and compared. Elango et al. [3] gave the theoretical analysis of simple and multi-effect solar still and explained the effect of the use of several materials on the rate of evaporation and efficiency of the stills. Tiwari et al. [4] gave analytical relations for glass and water temperatures for a multi-effect solar still. Al-Karaghouli and Alnaser [5] performed two experiments on a double-effect solar still with insulation and without insulation. They observed an increase in the production rate of freshwater for double solar still with insulation by 13%, whereas for non-insulated still, the rate of increase was 8%. Badran [6] studied the outcome of several parameters like water depth, the velocity of wind and surrounding temperature on the performance of single-slope conventional still. He found that output of solar still improved by 51% by the use of asphalt liner and sprinkler. Khalifa et al. [7] developed various performance correlations for simple solar still considering the influence of design, climatic and operational parameters. NarjesSetoodeh et al. [8] developed three-dimensional, multi-phase model to simulate the evaporation–condensation process in a conventional still by using CFD. Heat transfer coefficients for convection and evaporation were calculated and compared for experimental and CFD results. Badusha and Arjunan [9] also made a CFD model of solar still in order to model the process occurring inside it using ANSYS CFX, and the simulation results of coefficient of heat transfer, distilled water output and temperatures inside solar still were compared with the experimental results. Hitesh and Shah [10] also prepared a two-phase, three-dimensional model for the evaporation–condensation process in a solar still through ANSYS CFX to simulate the model. Rajaseenivasan et al. [11] conducted experiments to investigate the productivity of single- and double-basin solar still by considering effects of water depth, various wick, porous and energy storing materials. It was concluded that the production rate for double-effect still was 85% more than simple still under similar operating conditions. Vaibhav Khare et al. [12] developed multi-phase, three-dimensional model in CFD of single-slope single-effect solar still in ANSYS FLUENT to examine the efficiency of the still. He also performed parametric analysis to improve the productivity by use of different materials and also studied the impact of varying water depth on its thermal efficiency. Ithape et al. [13] studied different design and climatic parameters affecting the productivity of conventional still. Kalbasi et al. [14, 15] formulated a mathematical model to study the outcome of single- and double-basin solar still by use of heat and mass transfer relations.

Objectives

The main objectives of this paper are:

- Design and fabrication of a double-effect solar still to investigate the hourly distilled water output.
- To develop and simulate a two-phase three-dimensional CFD model of a double-effect still through ANSYS Workbench.
- To validate and compare the CFD model with the experimental results.

Experimental Investigation

Experimental Setup

The double-basin solar still unit is fabricated of two basins—upper and lower basin—each made up of plexiglass having 12 mm wall thickness. The shallow basins are covered by two condensing covers (glasses) which are also made up of plexiglass. The lower basin area is of 324 mm × 324 mm, whereas the upper basin has a dimension of 330 mm × 324 mm. The unit is insulated from all sides by using plastic foam (heat transfer coefficient = 2.5 W/m^2-K) to avoid any heat rejections to the surroundings. The bottom wall of lower basin and all side walls of both basins are painted black to improve absorptivity of solar radiations. The lower basin condensing cover is inclined at 8° and has a thickness of 12 mm to sustain the weight of water in the upper basin, whereas upper glass is 8-mm thick and is tilted at an angle of 18°, the latitude angle of Pune. The setup is kept in such a way that it faces towards the south, so as to capture maximum amount of solar radiations. The water level in the lower and upper basin is 4 cm and 6 cm, respectively. Figure 3 shows the photograph of the experimental setup. Five K-type (thermocouples) temperature sensors were used to measure temperatures of upper and lower glass temperatures (T_g), water temperatures in lower and upper basin (T_w) and the ambient temperature (T_{amb}), respectively.

Experimental Procedure

The experiment was run at MITCOE, Kothrud in Pune, India, having the latitude of 18.516°N and 73.856°E. The setup was kept facing north–south direction, so as to capture maximum amount of solar radiations. Required level of water was filled into the basins at the start of the experiment. The experiment was initiated at 9.00 a.m. and extended up to 5.00 p.m. For every 1 h, the ambient temperature, solar radiation intensity, upper and lower glass temperatures and the basin water temperatures were noted. Pure water was collected, measured and noted after each hour. At 05:00 p.m., the total distilled water output collected was measured.

Geometric Modelling and Mesh Generation

A virtual model of the problem domain in created in CFD modelling which is capable to obtain the required results. The model is discretized into small grids, and governing equations of mass, momentum and energy are solved at

Fig. 3 Photograph of the experimental setup

every grid. These equations are solved at every node by the CFD solver.

Geometric Modelling of Double-Basin Solar Still

A three-dimensional CAD model of double-basin solar still is designed using CATIA V5 in part modelling workbench. Figure 4 shows the CAD model of the double-basin solar still geometry.

Meshing of the Model

After geometry creation, the next step is to generate the mesh of the domain. Here, the problem domain is divided into a large number of small elements. The governing equations are solved for each of this element to simulate the physical phenomena. Figure 5 shows the meshing of the computational domain. Mesh independent study was carried out and found that the total number of elements in the meshed model is 304,632 and is sufficient as the geometry of the problem is quite simple. Here, hexahedral type of mesh is generated. Skewness, orthogonal quality, aspect ratio and element quality are some of the important parameters that determine the quality of mesh and have to be checked as they affect the accuracy of the solution to a large extent. For a good mesh, the skewness of each element must be close to 0, whereas orthogonal quality should be near to 1. Here, the average skewness of all elements is 0.08, whereas average orthogonal quality is 0.98. Also, the maximum aspect ratio is 5.53 which also indicate good quality mesh.

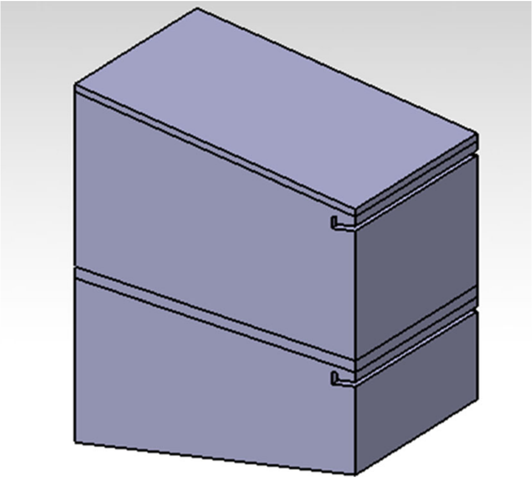


Fig. 4 Three-dimensional CAD model of solar still geometry

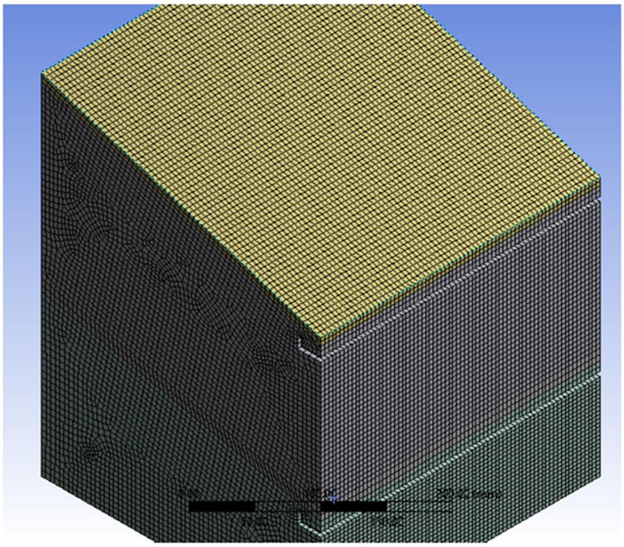


Fig. 5 Meshing of the domain

CFD Simulation

Boundary Conditions and Initial Conditions

Solar radiations fall on the upper glass, which then passes through it due to its transmissivity. Some of the absorbed radiations and latent heat of water from upper basin also pass through the lower glass to increase the temperature of water in the lower basin. Here, a three-dimensional, two-phase CFD model of double-effect solar still is developed using ANSYS FLUENT to understand evaporation–condensation phenomenon inside the still. The CFD simulation was run for 8 h starting from 9 a.m. Solar radiation intensity was defined by selecting the solar calculator with fair weather conditions which estimate the forecast value according to the latitude, longitude and GMT of the working area. Physical and thermal properties of materials (plexiglass, air, water–liquid and water–vapour) such as density, specific heat capacity and thermal conductivity used in the simulation were specified. Most of the boundary conditions are determined by the physical phenomena but some are set by the simulation software. Table 1 shows the various boundary types and boundary conditions specified on the geometric model.

Multi-phase VOF (volume of fluid) model with three phases, namely air, water–liquid and water–vapour, are defined to model the evaporation–condensation process. Turbulence model used is RNG (renormalization group) k-epsilon with standard wall function. Side walls are insulated; hence, adiabatic wall conditions are applied. Adhesion forces are considered during analysis for producing water droplets on the inner wall surface of condensing glass. Air and water volume fractions are specified as 0.75 and 0.25, respectively. Operating pressure and

Table 1 Boundary conditions and types

Zone name	Zone type	Description	Wall thickness (m)
Front_walls	Wall	Adiabatic wall (heat flux = 0)	0.012
Side_walls	Wall	Adiabatic wall	0.012
Bottom_wall	Wall	Adiabatic wall	0.012
Back_walls	Wall	Adiabatic wall	0.012
Upper_glass	Wall	Convection & radiation (solar ray tracing)	0.008
Lower_glass	Wall	Convection and radiation	0.012

temperature are taken as 1.01 bar and 300 K, respectively, with gravity in the negative *Y* direction. First-order upwind method is used for momentum, energy, volume fraction, kinetic energy and dissipation rate as it gives a stable solution with a good rate of residual convergence. The convergence criterion for energy equation is set to 10^{-6}, whereas for all other variables such as *X*, *Y* and *Z* velocity, continuity, energy, turbulent kinetic energy (k) and kinetic energy dissipation rate (ε), convergence criteria are taken as 10^{-3}.

Simulation Results

ANSYS FLUENT v16.0 is used as a solver to simulate the CFD analysis. Transient simulation of solar still was carried out on 3 May from 09:00 to 17:00 h. In case of a solar still, temperatures attained by glass covers, water in the basins and the interior of the still play a vital role for the distillation of water. Various contours of static temperatures and volume fraction of water phase have been plotted at different time intervals. For validation of the CFD model, simulation results are compared with the experiment performed on 3 May 2018 at MITCOE, Pune. The temperature contours of upper and lower glass are plotted for every hour. It has been observed that these temperatures go on increasing up to 02:00 p.m. and then, further decrease with the increase in time. This is because solar radiation intensity increases up to 14:00 h, after which it decreases monotonically. So glass temperatures also follow similar pattern to that of solar intensity falling on the glasses. From the contours of upper glass temperatures, it can also be noticed that temperatures on the lower end of the glass are relatively less than temperatures at the upper part of the glass. This is because pure water slides through the inner wall surface from the upper part to the lower end of the glass.

The contours of interior water temperature are also plotted for the interval of every 1 h. Within the solar still, it is noticed that the temperature of water begins to rise as the solar radiations fall onto the water in the basin. After some time, water starts heating and evaporation takes place which results in the formation of vapour as well as an increase in the interior temperature. Contours of interior temperature show increment in the interior temperature of solar still with time. The average of glass and water temperatures in both basins are used for calculating convective and evaporative heat transfer coefficients and distillate output rate using equations given in Ref. [2].

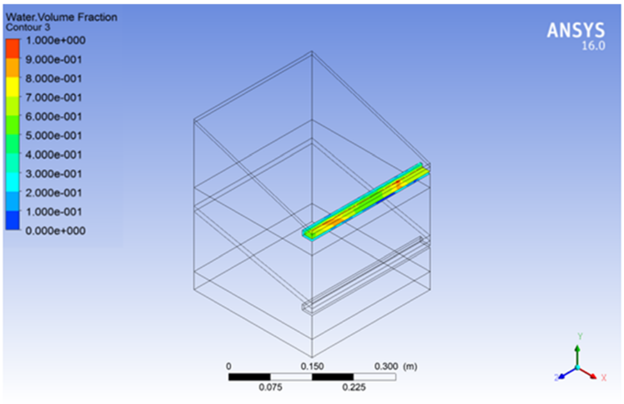


Fig. 6 Water volume fraction at the output in the upper basin

Figures 6 and 7 show contours of water volume fraction at distillate channel for upper and lower basin, respectively. Water volume fraction in the distillate channel is nearly 0.7 which indicates that the distillate water gets accumulated in the channel after sliding down from the tilted glass surface.

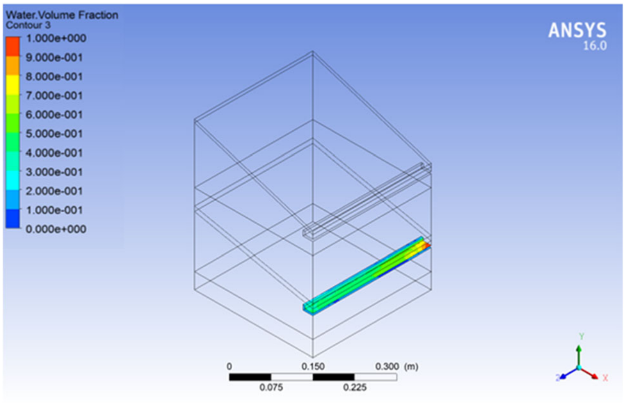


Fig. 7 Water volume fraction at the output in the lower basin

Fig. 8 Upper glass temperature variation with time

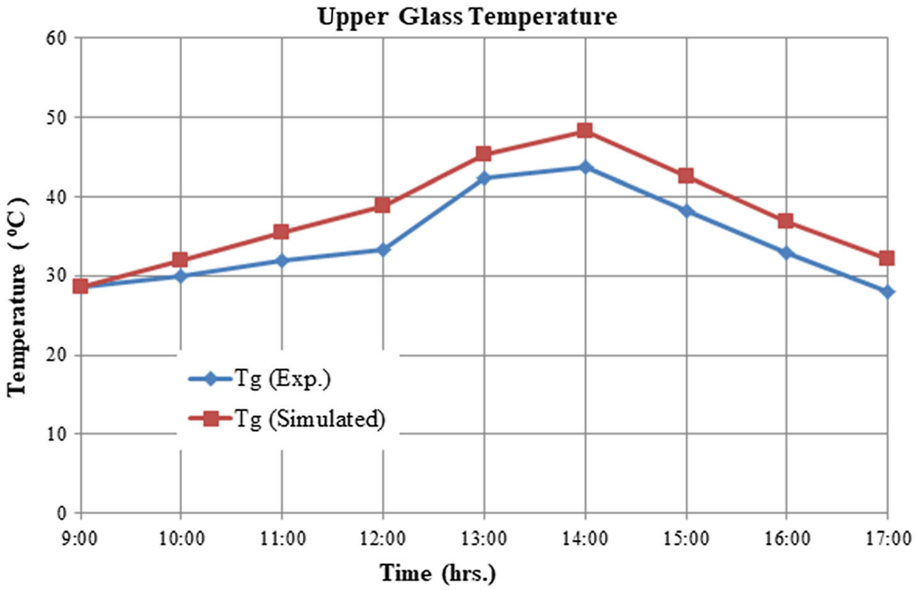
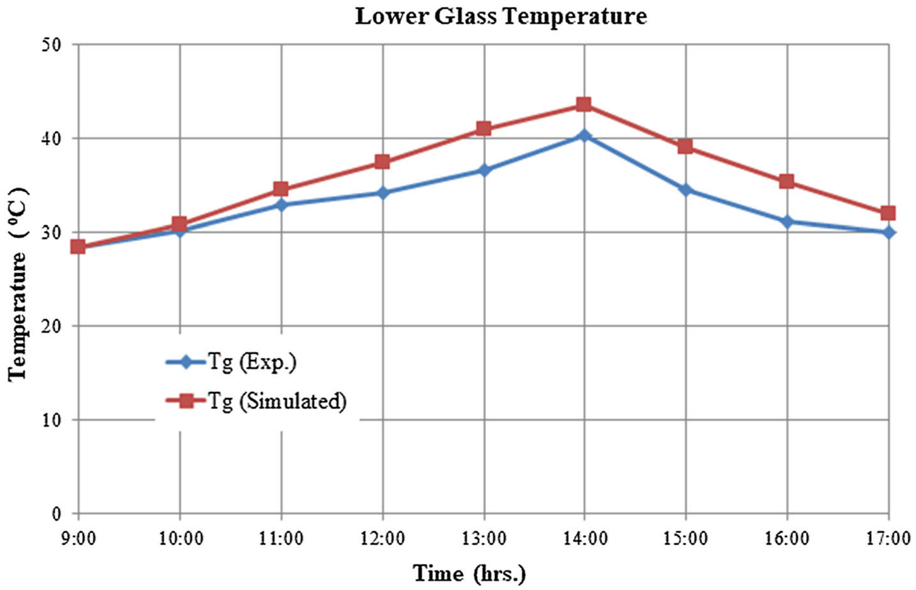


Fig. 9 Lower glass temperature variation with time



Validation of the Model

For the validation of the CFD model of passive double-effect solar still, experimental data of the glass temperatures and water temperatures taken on 3 May 2018 are used for the comparison with the simulated temperature data. It has been observed that the simulations results deviate by 5–12% due to the following plausible reasons: (a) Adiabatic walls are assumed in simulations, whereas in actual, there is some heat loss through the walls. (b) In experimentation, the water condensed on glass surface created hindrance to solar rays reaching to the basin water, whereas in simulations, its effect is neglected. (c) Wind velocity over solar still was considered to be negligible.

Figures 8 and 9 show the variation of glass cover temperatures with the time of the day. It can be noted that the glass cover temperatures increase from 09:00 to 14:00 h about monotonically and after that it decreases. This trend is expected as it is analogous with the trend of solar radiations intensity.

Figures 10 and 11 show the comparison between experimental and simulated values of water temperatures in upper and lower basins. Since the basin water takes necessary energy required for evaporation from solar radiations, the temperature of water also follows a similar trend of solar radiation intensity.

Figures 8, 9, 10 and 11 show the comparison between the simulated and experimental values of upper and lower glass and water temperatures. However, both experimental

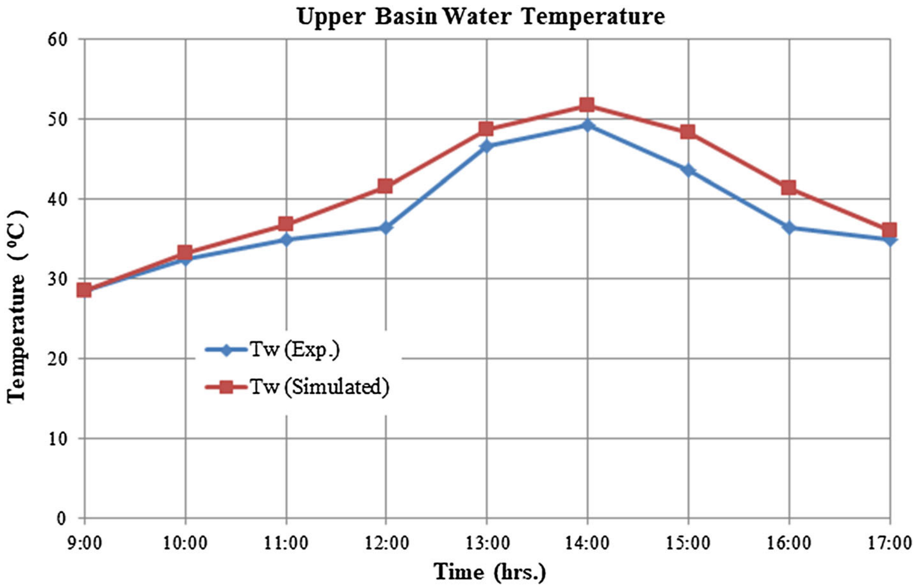


Fig. 10 Upper basin water temperature variation with time

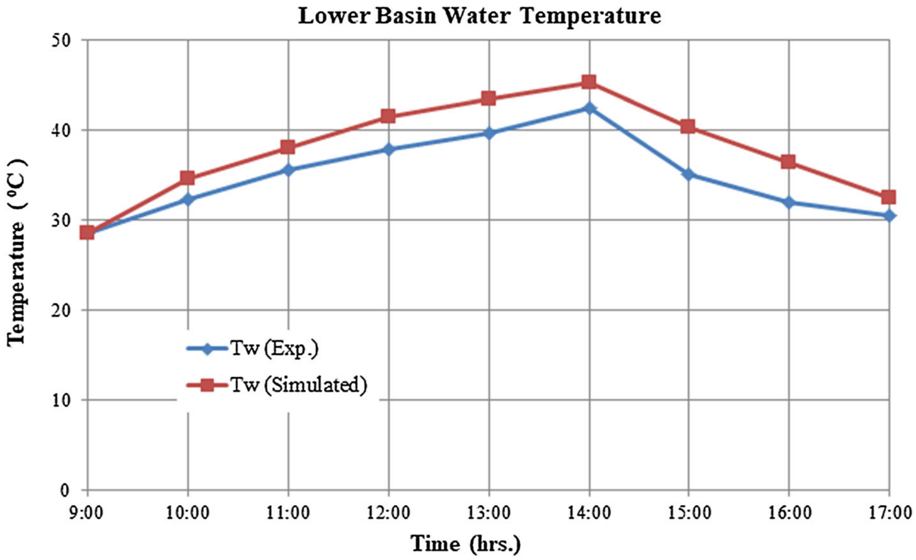


Fig. 11 Lower basin water temperature variation with time

and simulated results follow the same pattern; there is a small difference between the two values at each step of time. This difference is attributable to the fact that the CFD tool considers the ideal characteristics of the material such as glass which may differ from its actual properties that are used in the experiment. Also, there is no consideration of natural attenuation in simulation results which is also a factor that induces the difference between the two values.

Figure 12 shows the comparison of cumulative water output values from CFD and the experimental data. Simulated results are based on the values calculated through equations given in [2, 3] from CFD data. From the comparison, it can be said that CFD prediction and experimental results are in good agreement.

Conclusion

The main objective of this study was to perform experimental investigations, develop a three-dimensional CFD model of double-basin passive solar still and compare simulation and experimental results. The experimental setup was made ready as per the required dimensions. Upper and lower glass temperatures, the water temperature in both basins and ambient temperature were measured at every hour after the experiment was initiated at 09:00 h. Then, a three-dimensional geometric model of solar still was developed in CATIA through part modelling. The appropriate models were then selected for the physical phenomena occurring in the solar still. Material properties and appropriate boundary conditions were defined in

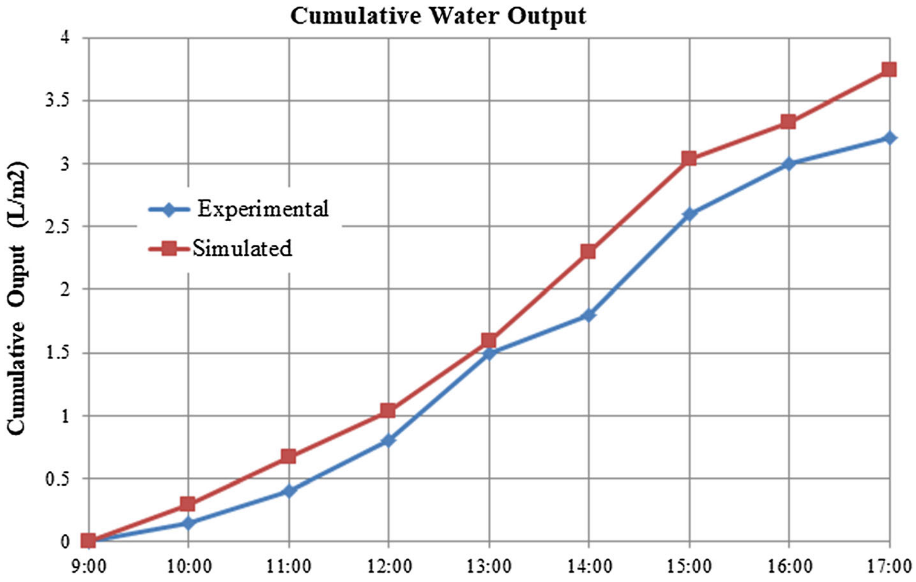


Fig. 12 Cumulative water output

FLUENT for simulation of the problem. Simulations were conducted for unsteady state conditions with the FLUENT solver on 3 May. CFD simulation results were compared with the experimentation conducted on 3 May 2018.

The following conclusions were made from experimental data and CFD simulations:

- Multi-basin solar still has higher distillate output in comparison with simple solar still [5] as it utilizes latent heat of condensation to raise the temperature of water in the upper basin.
- Glass temperatures increase with time from 09:00 a.m. up to 02:00 p.m. as solar radiation intensity increases and further decreases as time proceeds. Hence, it can be said that they follow a similar trend to that of solar radiations.
- The contours of glass temperatures also show that temperatures on the lower end of condensing glass are relatively less than the temperatures at the upper part of the glass. This is because freshwater slides down on the inner wall surface from upper part to the lower side of the glass cover.
- Distilled water output collected is calculated from temperatures and heat transfer coefficients and captured through simulations and by using equations from [2, 3].
- Experimental investigations show a total distilled water of 3.2 L/m^2 collected in output channel, whereas CFD results show 3.74 L/m^{2}as total output. Hence, it can be said that there is a good compliance between simulation results and experimental data captured for distillate yield.

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