Iranian Journal of Mechanical Engineering
The Iranian Society of Mechanical Engineers
Research Paper

**DOI: 10.30506/JMEE.2022.535108.1267**

# Numerical Modeling and Analysis of the Performance of a Stepped Solar Still using Multi-phase Method

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*The modeling of solar stills using CFD is a quick and low-cost way of designing and optimizing these systems. So far, only basin-type solar stills have been numerically analyzed; and it is the first time that a 3-D stepped solar still model has been numerically analyzed in the present work. A 3-D and 3-phase numerical model of a stepped solar still is presented in this research. The exterior of this solar still is exposed to ambient temperature and pressure. The initial conditions and temperatures of the system have been determined by an experimental test. The validation results of the present numerical model have a good agreement with former empirical results. The amount of error between numerical and empirical results varies at different times of the day. At early hours, the difference between the water temperatures obtained by modeling and by experimentation is only 1.6%, which rises to 11.7% at later hours of the day. This amount of discrepancy is due to the change that occurs in the behavior of solar still under ambient conditions.*

*Keywords:* Stepped solar still, Computational fluid dynamics, 3D modeling, 3-phase model

## 1 Introduction

Potable water shortage is the foremost concern of human communities around the globe. The major water resources in the world include the saline waters in oceans and seas, while many sources of fresh and potable water are contaminated by a variety of pollutants. These contaminants, including the residues of chemical compounds, household and industrial sewage, various types of garbage, and many other pollutants, make it impossible to utilize such potable water resources. Iran is among the countries with a dry and arid climate and very low precipitation. Currently, with the constant decline of subterranean water resources and the expansion of drought, people in many areas of Iran are facing the drinking water shortage. Also, with the decrease of water flow in many rivers and their contamination in certain regions, agricultural lands under cultivation have shrunk threatening food production. This is while in

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Receive: 2021/08/01 Accepted: 2022/04/18

many deprived regions there is a good potential for using solar energy to desalinate and purify undrinkable brackish water into potable water. Considering the large number of sunny days in a year, such processes would be feasible and cost-effective in underprivileged areas. The sun is a permanent, economical, and pollution-free source of energy. Solar stills have low manufacturing costs and require no source of power to operate other than the direct energy of the sun. This characteristic makes the use of solar stills cost-effective in deprived regions with a large number of sunny days in a year.

One type of solar stills that operate by direct method is the simple (single-stage) condensing still. There is a variety of these stills, one of which is the stepped solar still. These solar stills operate based on the fundamental laws of water condensation. Undrinkable saline water enters the steps of the still unit, where it is heated and vaporized by solar radiation. During evaporation, the existing impurities, contaminants, and even some microbes are separated from water molecules and left behind on the steps. The pure and contaminant-free water molecules then move upward in the form of vapor. These distillation systems are mostly covered with glass or plastic. Therefore, water vapor cannot escape the still and it eventually condenses underneath the inclined surface overhead, which conveys the condensed water droplets to the system outlet. The stepped type of solar still is more efficient than the pool-type; because in the former, due to a smaller space between saline water level and the top glass cover, the condensation process and cycle is faster and takes less time. This leads to a higher distilled water production efficiency.

To reduce the cost of building a prototype and performing experimental tests, computational fluid dynamics (CFD) can be employed to model a solar still. In recent years, pool-type solar stills have been numerically modeled by different techniques. Most of these studies have employed two-phase models. Using the “Fluent” software, Ahmad et al. [1] presented a 2D model for a pool-type solar still under vacuum. In this modeling, they explored the effects of vapor pressure and water height. They discovered that by increasing the vapor pressure and the height of the still unit, the amount of distilled water produced by the system diminishes, and vice versa. Setoodeh et al. [2] employed the “CFX” software program to perform a two-phase 3D modeling of a pool-type solar still system. They compared their results with those of an experimental test and found good agreement between the two. Panchal et al. [3] presented a 3D model of a pool-type solar still and compared its results with empirical data. Using the “CFX” software program, Badusha et al. [4] modeled a one-way pool-type solar still and compared its parameters such as water temperature and distilled water productivity with experimental results. Rahbar et al. [5] employed the "Fluent" software package to model a tubular solar still. Their research showed that the maximum rate of water condensation occurs at the highest point of the top glass cover. They achieved a 250% increase in the production of distilled water by raising the water temperature by 5 ºC. Mahesvari et al. [6] presented a 3D model of a two-way pool-type solar still. They used the “CFX” software program to model and analyze the considered still system in their research. They also compared their numerical results with the test results of an actual prototype for different months of the year and obtained the amount of distilled water produced in each month. Employing the “Fluent” software package, Rashidi et al. [7] investigated a 2D model of a pool-type solar still and used a nanofluid in their analysis. In this modeling, they compared the behaviors of pure water and water mixed with nanoparticles. Their findings revealed a higher evaporation rate in the still system that utilized a nanofluid. Rai-Khar et al. [8] used the “Fluent” software program and performed a 2D modeling to simulate and analyze a pool-type solar still unit. Also, Rashidi et al. [9] studied a stepped solar still via 2D modeling. They found out that the distilled water output of this still system is mainly influenced by the width of steps at small scales and by the height of steps at larger scales. T.Yan et al. [10] used computational fluid dynamics modelling to investigate the effects of operating pressure and geometrical parameters on the performance of a Tubular Solar Still. The simulation results indicated that water vapor has a higher circulation velocity when operated under vacuum

compared with atmospheric conditions, resulting that the yield rate increased by more than 50%. M. Keshtkar, et al. [11] developed a transient CFD model to investigate the parameters affecting the productivity of a solar still. This simulation showed that a 14.4% increase in the productivity is observed when the wind speed increases from 1 m/s to 6 m/s, and a 3.5% improvement occurs by decreasing the glass thickness from 4 mm to 2 mm.
A review of existing literature shows that all the former research works have been conducted on pool-type stills and the stepped solar still systems have been investigated by 2D modeling. Also, in most of the previous research works, the boundary conditions for the modeled stills, including glass cover temperature and bottom temperature, at every operating hour, have been considered as constant. In the present research, a 3D, 3-phase numerical modeling of a stepped solar still unit has been implemented using the “ANSYS Fluent” software program. After modeling and meshing the examined still system, it has been analyzed at different operating hours. A stepped solar still has been constructed and used for modeling and validation purposes (Fig. 1). The experimental model includes a one-way stepped solar still, a parabolic trough solar collector consisting of a small-size evacuated glass tube, and a semi-cylindrical mirror under the vacuum tube and two flat reflectors above and below the still unit. A storage tank of saline water is installed behind the still, which is connected to the evacuated glass tube. The performance of the stepped solar still was inspected from 8 A.M. to 5 P.M. The temperatures of step treads, the glass cover, the water flowing on the steps along with the amount of produced distilled water and solar radiation intensity were recorded on an hourly basis [12]. The solar still in the experiment is an active type. Both active and passive modes of the equipment were tested in the experimental work, but the results of the passive mode of the equipment were used for validation. In the passive mode, the trough collector and the flat reflectors were covered in order to solely analyze the performance of the steps. The modelled still geometry has the same dimensions and sizes of the still system which was constructed and tested previously, and all the initial and boundary conditions, as well as the ambient conditions considered in this modelling, match those in the experiment work.

## 2 Geometry and meshing of the still model

The stepped solar still analyzed in this research is similar to the system tested in the experiment work. This still unit has 10 steps for receiving inlet saline water and one step at the end for collecting the produced distilled water. The width of the analyzed still is 50 cm and the top glass cover over the steps is inclined at 35º, in proportion to the latitude of the city of Karaj (Iran). The geometry of the still system includes two separate volumes called pool and collector, with the possibility of heat and mass transfers between them. This arrangement has been implemented to make it simpler for the software to measure the amount of output distilled water at the end section of the still unit.

**Figure 1** The solar still system used for simulation and validation

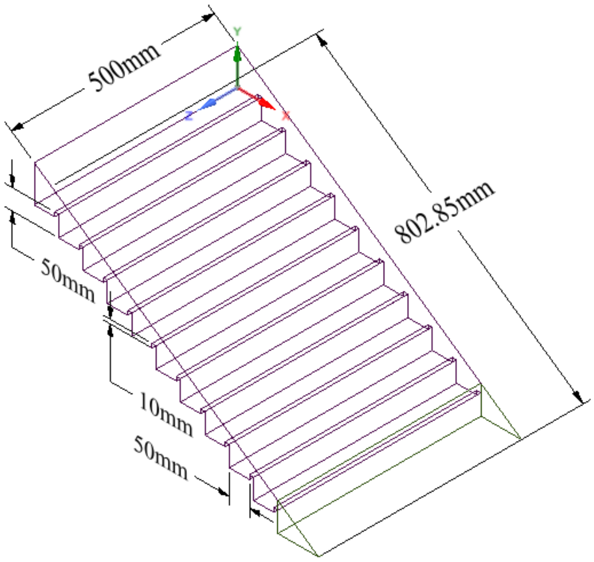



**Figure 2** The geometry of the examined stepped solar still

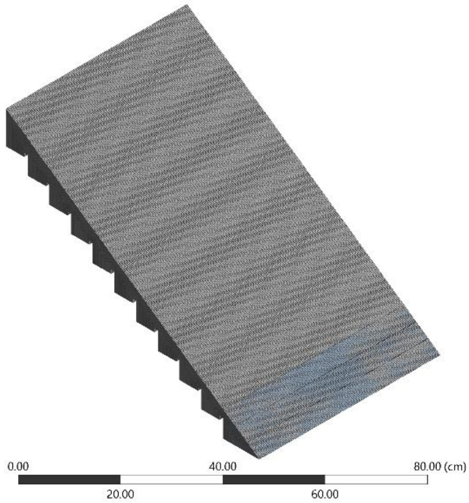



**Figure 3** Meshing of the solar still model

To perform an exact analysis, the volume of accumulated water in the solar still should be properly meshed. For this purpose, the height of the water within the still [over the steps of still] has meshed with 10 vertical meshes to a total height of 1 *cm*. Square type meshes have been used in the process, and the number of nodes in the still geometry is 506748. The overall volume of the still unit is 19250 $cm^3$. The width of each step is 5 *cm* and there is a 1 *cm* tall edge in front of each step. The width of the last step is 15 *cm*, and the solar still has a height of 40 *cm*. The whole region of the model geometry is defined as fluid. The steps of the examined solar still are made of aluminum and its top cover is 3*mm*-thick glass. All the walls of the still system are assumed to be adiabatic. Figs. (2) and (3) illustrate the model geometry and meshing in the present work.

## 3 Governing equations

The energy equations for gas and liquid phases in the examined solar still are expressed as Eq. (1) and Eq. (2), respectively.

$$\nabla.(r_g\rho_g v_g h_g) = -\nabla.q + (Q_{lg} + S_{lg}h_{lg}) \quad (1)$$

$$\nabla.(r_l\rho_l v_l h_l) = -\nabla.q - (Q_{lg} + S_{lg}h_{lg}) \quad (2)$$

In the above equations, ρ, h, r, Q, S, q, and v respectively represent density, specific enthalpy, volume fraction, heat transfer flux, mass transfer flux, flux of enthalpy, and velocity. Moreover, Eq. (3) is used to calculate the volume fractions of water and vapor.

$$r_g + r_l = 1 \quad (3)$$

The liquid and gas phases have the same pressure, which is computed by Eq. (4) [2].

$$P_g = P_l = P \quad (4)$$

The heat transfer between liquid and gas phases is obtained from Eq. (5).

$$Q_{lg} = -Q_{gl} \quad (5)$$

Similarly, the mass transfer equations for the two phases of liquid and gas are expressed as Eq. (6) and Eq. (7), respectively.

$$\nabla.[r_g(\rho_g v_g Y - \rho_g D_g(\nabla Y))] - S_{lg} = 0 \quad (6)$$

$$\nabla.[r_l(\rho_l v_l X - \rho_l D_l(\nabla X))] + S_{lg} = 0 \quad (7)$$

In the above equations, Y and D denote mass fraction and diffusion coefficient, respectively; and the continuity equations for the two phases of fluid are represented as Eqs. (8) and (9).

$$\nabla.(r_g\rho_g v_g) + S_{lg=0} \quad (8)$$

$$\nabla.(r_l\rho_l v_l) - S_{lg=0} \quad (9)$$

The amount of distilled water produced by the stepped solar still is an important parameter for determining its performance and is computed by Eq. (10).

$$\dot{m}_g = -\dot{m}_l = \frac{2k_l(\nabla r_l.\nabla T)}{h_{lg}} \quad (10)$$

In this equation, $\dot{m}$, k, $h_{lg}$ and T are the distillate output, conduction heat transfer coefficient, latent heat of vaporization, and water temperature, respectively.

## 4 Modeling assumptions

In modeling the solar still system, the following assumptions have been considered:

- All the walls of the system have been considered as adiabatic.
- The problem has been analyzed as a 3-phase process.
- The initial temperature and pressure of the system have been set equal to ambient temperature and pressure.
- Wind velocity has been considered as zero

## 5 Solution method and boundary conditions

For solving the problem, the VOF model with 3 phases of water, air, and water vapor has been considered. The VOF model is used for two or several unmixable fluids, and the interface between two fluids is an important parameter in this model. In the VOF model, a series of momentum equations is considered for the fluids, and the volume fraction of each fluid phase is obtained for each cell. This model is used when there is laminar flow or free surface. Gravitational acceleration has been considered in solving the problem, and the modeling has been performed by employing $k-\varepsilon$ equations transiently. The "SIMPLE" algorithm and the second-order upwind approach have been used for the problem. In addition, residuals were set to $10^{-6}$ for energy equation and $10^{-3}$ for continuity, momentum, k, and ε equations. The modeling of solar radiation has been implemented for the position and latitude of the city of Karaj by using the existing model in the software program. The geographical position and the test days and hours in the software have been set equal to those in the experiment work. Heat and mass transfers have been considered in analyzing the problem. An initial volume of saline water, with a depth of 1 *cm*, is considered to exist on each of the 10 steps of the solar still and this quantity of water is added to the geometry at the beginning of every modeling cycle. For this purpose, at the onset of every modeling cycle for one hour, 10 different zones are defined and the mass ratio of water in these regions is set equal to 1. In analyzing the problem, phase changes from liquid water to vapor and from vapor to liquid are defined in the software. Also, surface tension is applied between all three phases. At the start of the solution, there are only two phases of water and air in the model geometry. With the elapse of time and the onset of the evaporation process, the vapor phase is also added to those two phases. A PC system with a 4-core 2.4 GHz processor and 6 GB of RAM has been used for analysis. Due to hardware limitations, for modeling the operation of the examined stepped solar still for one day, the analysis should be divided into one-hour phases.

## 6 Mesh-independency evaluation

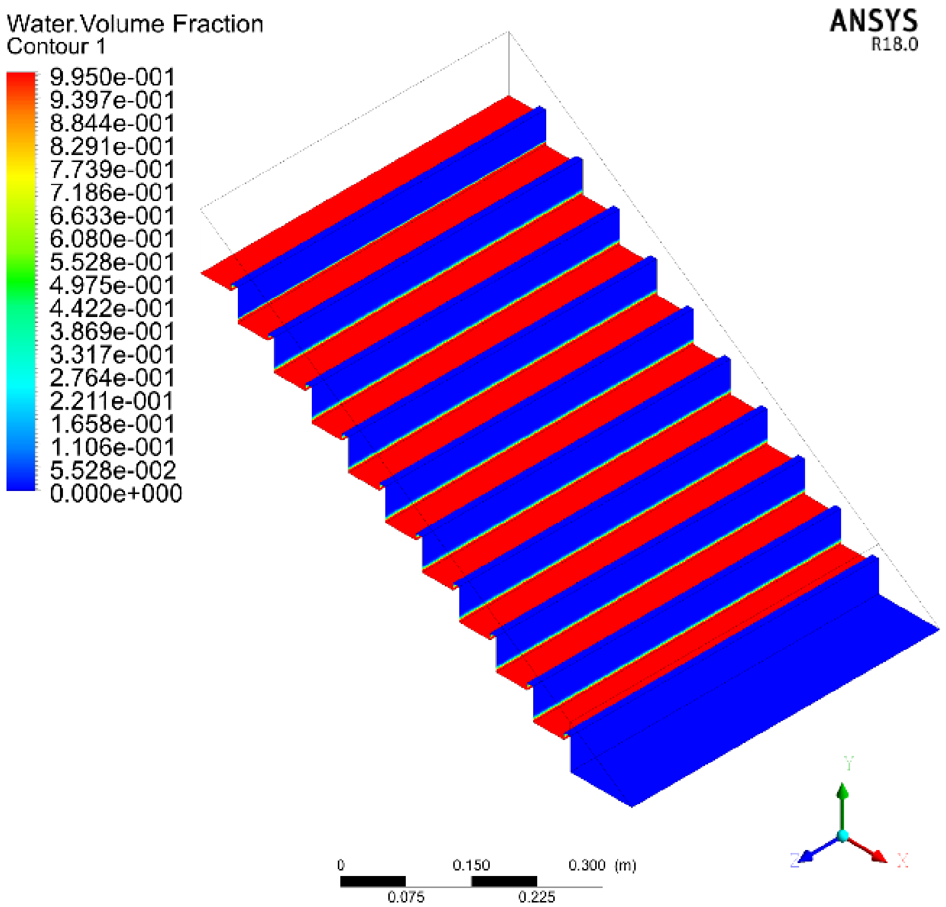
To evaluate the mesh-independency of solution, first, the geometry of the still system meshed with 260326 square type elements, and the solution yielded hourly distilled water production of 0.652 ml. Then the geometry meshed with 389062 elements, and the solution produced hourly distilled water output of 0.487 ml. Finally, the geometry meshed with 506748 elements, and an hourly distilled water production of 0.472 ml was obtained. It was observed that by using finer meshes in succeeding steps, the obtained results vary very little relative to the preceding step. Although there is a closer match in the results by further increasing the number of applied meshes, the volume of data to be processed, and the modeling time also increase at the same rate. Thus, because of the above results, 506748 meshes were used in solving the problem. Table (1) shows the steps taken to confirm the mesh-independency of solution.

**Table 1** Mesh-independency evaluation

| Mesh numbers | Distilled water (ml) | Change rate (%) |
|---|---|---|
| 260326 | 0.65283 | - |
| 389062 | 0.48719 | %34 |
| 506748 | 0.47209 | %3.2 |

## 7 Results

In the present research, the obtained data have been validated by the empirical results of the experiment work. In this analysis, the amount of distilled water produced and the behaviors of all three phases have been investigated within one day. The volume fraction contours of water on the steps and glass cover of the examined solar still can be observed in Figs. (4) and (5). According to Fig. (4), which shows the behavior of water on the steps of the system at both initial and final condition, water has evaporated completely on some steps, but is still flowing over the other steps. The evaporated water condenses on the glass cover, the water drops then roll down and is collected on the last step of the still unit. The volume fraction contour of water on the glass cover of solar still has been illustrated in Fig. (5). Due to the small volume fractions of water drops formed on the glass cover, the range of volume fraction has been limited to [0, 0.0001] so that water droplets can be better observed. Because the top glass cover is tilted downwards, the condensed water droplets slide down on it; and, therefore, the concentration of water drops on the lower sections of glass is greater than other parts. An overall temperature distribution within the still system has been illustrated in Fig. (6).



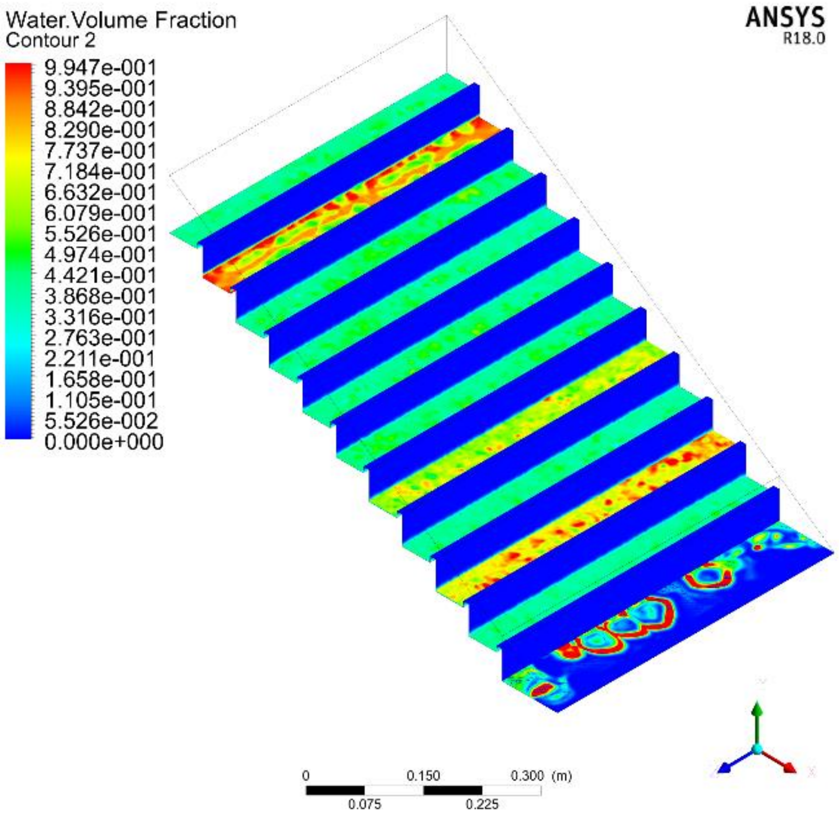



**Figure 4** Volume fraction contour of water on the steps of solar still

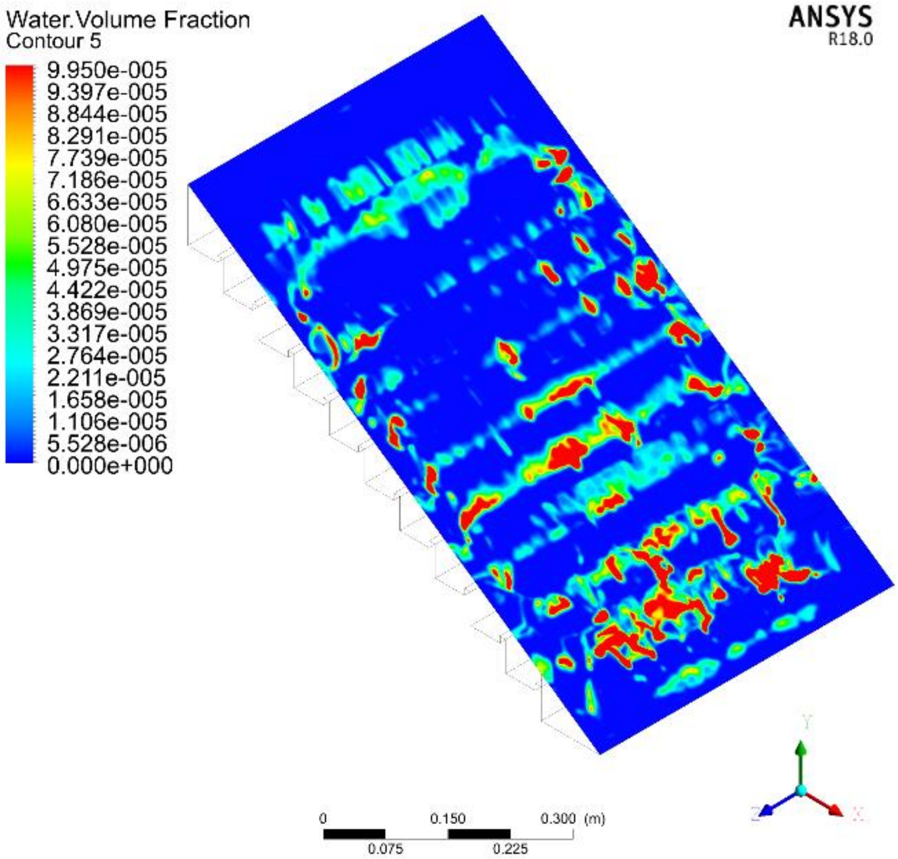



**Figure 5** Volume fraction contour of water on the glass cover of solar still

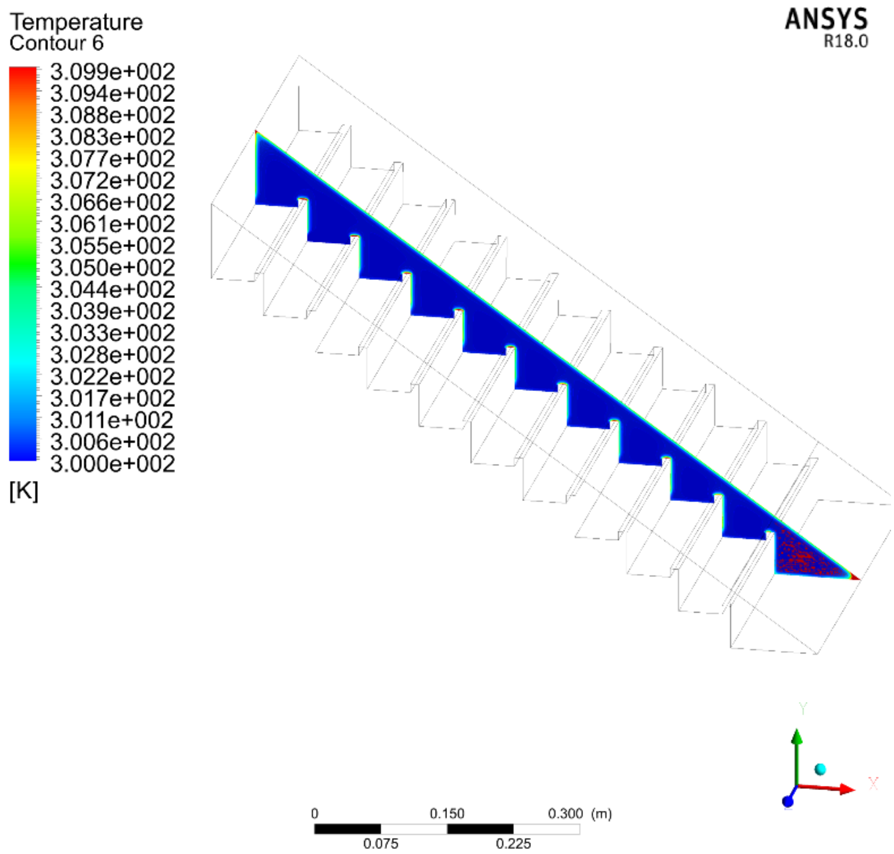



**Figure 6** Contour of temperature distribution within the solar still unit

As the above figures indicate, the contours have a good agreement with the modeling results mentioned at the beginning of the paper. The volume fraction of water is separate from the air phase, and the boundary between the two is distinguishable. As the temperature inside the still unit rises, water evaporates gradually and condenses on the top glass cover due to temperature difference. The condensed droplets then roll down on the glass surface and are eventually collected on the last step of the still. The distilled water output can also be observed in the contour related to the volume fraction of water. Following the evaporation of water, the glass temperature gradually reaches 49 ºC and then goes down. The temperature distribution contour clearly shows the temperature difference between step surface and glass, which ranges from 31 to 68 ºC. The trend of the errors obtained for different parameters has been shown in Table (2). As is observed, the errors obtained for the early hours of modeling are less than those for the later hours. This is due to the discrepancies and differences that exist between modeling and experimentation. Conditions such as wind gust, shadows cast by passing clouds over the still unit, the possibility of tiny leakages in the system, precipitations formed on the bottom of the still, and measuring errors caused by humans are some of the parameters that are disregarded in modeling, because of simplifying the problem. The variations of step temperature, glass temperature, and water temperature have been illustrated in the diagrams of Figs. (7), (8), and (9). As previously mentioned, due to the parameters that affect ambient conditions, the error values for the early hours of modeling are less than those for the later hours. The hourly distilled water output of the system has been displayed in Fig. (10). The amount of distilled water produced in the simulation process during each operating hour is less than that obtained in the experiment. This discrepancy is caused by the walls of the system being considered as adiabatic during simulation, the difference between the modeled radiation of the sun and the actual radiation, the elimination of environmental parameters such as wind velocity in ambient conditions, and other factors of this nature.

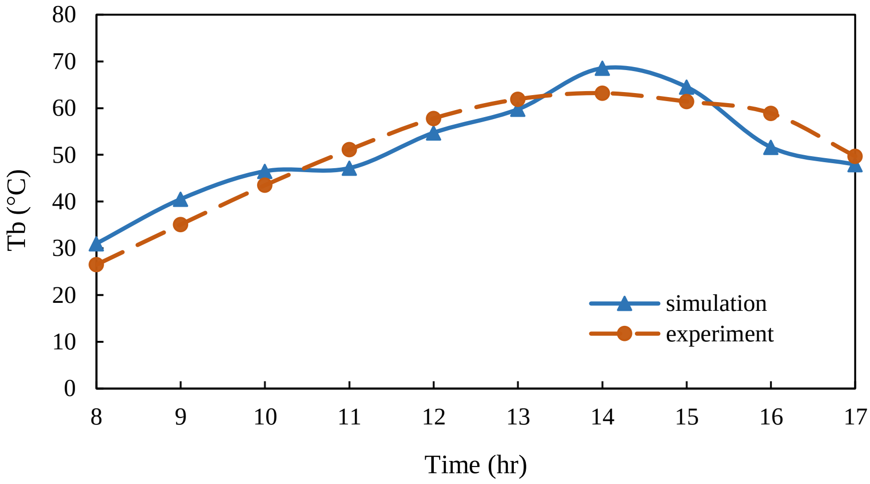



**Figure 7** Variation of steps temperature with time

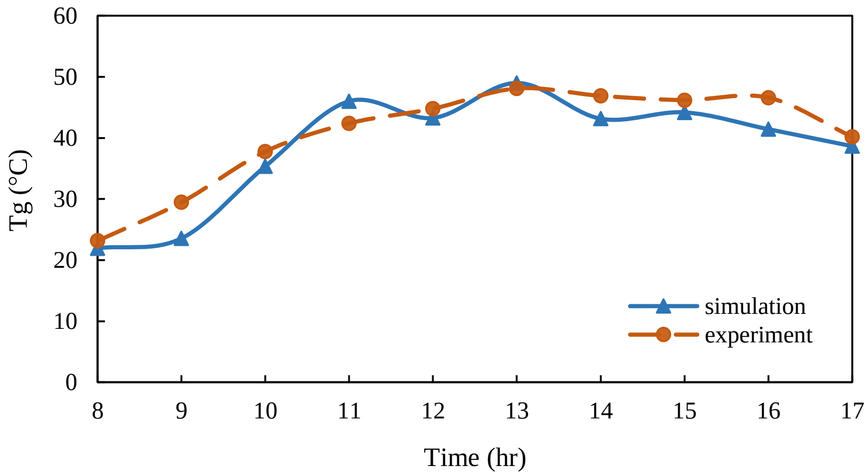



**Figure 8** Variation of glass cover temperature with time

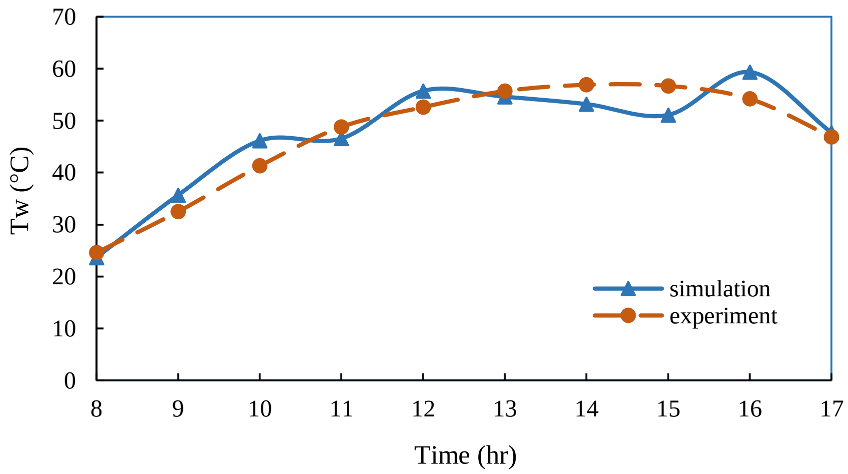



**Figure 9** Variation of water temperature with time

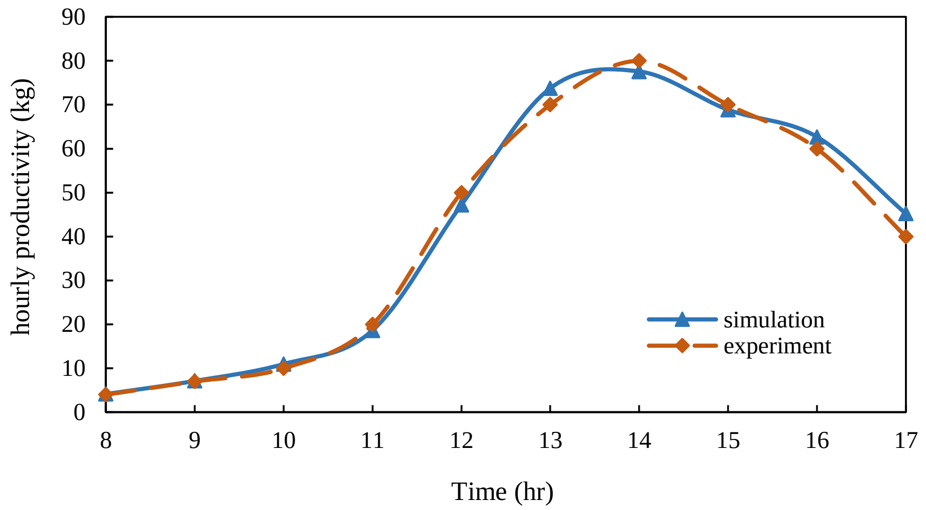



**Figure 10** Distilled water output versus time

**Table 2** Output errors (%) at different operating hours

| Hour | Distilled water output | Water temperature | Step temperature | Glass temperature |
|---|---|---|---|---|
| 8 | 3.574 | 3.847 | 16.981 | 5.350 |
| 9 | 1.751 | 9.719 | 15.434 | 20.089 |
| 10 | 9.744 | 11.719 | 6.874 | 6.409 |
| 11 | 6.847 | 4.595 | 7.706 | 8.577 |
| 12 | 5.581 | 5.918 | 5.318 | 3.367 |
| 13 | 5.339 | 2.007 | 3.471 | 1.922 |
| 14 | 3.053 | 6.553 | 8.424 | 7.971 |
| 15 | 1.647 | 9.892 | 5.083 | 4.325 |
| 16 | 4.472 | 9.472 | 12.350 | 11.052 |
| 17 | 13.064 | 1.685 | 3.605 | 3.811 |
| average | 5.507 | 6.541 | 8.525 | 7.287 |

The results show that the amount of distilled water output obtained by simulation differs a little from the experimental result, but the error value is acceptable. The minimum and the maximum errors obtained for water temperature are 1.6% and 11.7%, respectively. The lowest and the highest percentages of error for glass temperature are 1.92% and 20.08%, respectively. Also, the smallest and the largest error values obtained for the temperature of still bottom are 3.47% and 16.98%, respectively. As was mentioned before, the discrepancy between theoretical and experimental results could arise from environmental conditions, software limitations, and the fluctuations in the behavior of the still system under ambient conditions, which are not considered in computer analysis. Similar to actual experiments, in the performed simulation, very little distilled water is produced at the early hours of the day, which increases at noon and afternoon hours, as solar radiation intensifies. The minimum and the maximum errors obtained for the amount of distilled water produced in simulation are 1.64% and 13.06%, respectively. The validation of results indicates that this type of modeling can be employed in future research works to study the behavior of stepped solar stills in various seasons of the year. This modeling procedure can also be extended to different solar still geometries.

## 8 Conclusion

In this research, the processes of water evaporation and condensation inside a stepped solar still system have been modeled and analyzed in 3D and 3 phases (water, water vapor, and air). A review of previous works reveals that all former CFD-based modeling works have been conducted on basin-type stills, and that most studies of pool-type stepped solar stills have used 2D models. The contours obtained in this paper agree well with those in former works, and the behavior of the liquid water phase in this research is similar to that in previous works. The findings of this research are as follows:

1- The average error values obtained by the present method for the temperature of the water inside the still, temperature of top glass cover, and the temperature of step surfaces are 6.54, 7.28, and 8.52%, respectively.

2- The average error obtained for the distilled water output of the stepped solar still is 5.5%; which is mainly due to the ambient conditions prevailing in the actual test site.

3- The amount of error obtained by this method is small at the early hours of modeling, but increases at late hours; this is also due to the ambient conditions.

4- This method can be used in future research works to model more complicated mechanisms and processes of evaporation and condensation.

## Acknowledgment

The authors of this paper wish to thank Mr. Mohammad Sadegh Mirloo (Mechanical Engineering expert at the Islamic Azad University in Karaj) for his invaluable help and cooperation with the project.

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**Nomenclature**

| | |
|---|---|
| $D_g$ | Diffusion coefficient of gas phase, m/s$^2$ |
| $D_l$ | Diffusion coefficient of liquid phase, m/s$^2$ |
| $h$ | Specific enthalpy, J/kg |
| $k$ | Thermal conductivity, W/m°C |
| $\dot{m}$ | Distillate output, kg |
| $P$ | Pressure, N/m2 |
| $Q_{lg}$ | Heat transfer between liquid and gas phases, W/m$^3$ |
| $q$ | Flux of enthalpy, W/m$^2$ |
| $r$ | Volume fraction, dimensionless |
| $S_{lg}$ | Rate of interphase mass transfer, kg/m$^3$s |
| $T$ | Temperature, °C |
| $v$ | Velocity, m/s |
| $X$ | Mass fraction of liquid phase |
| $Y$ | Mass fraction of gas phase |

*Greek symbols*

| | |
|---|---|
| $\rho$ | Density, kg/m$^3$ |

Subscripts

| | |
|---|---|
| $g$ | Gas |
| $l$ | Liquid |