JOURNAL OF MECHANICAL ENGINEERING AND SCIENCES
ISSN: 2289-4659 e-ISSN: 2231-8380
VOLUME 17, ISSUE 2, 2023, 9433 – 9442
DOI: https://doi.org/10.15282/jmes.17.2.2023.2.0746

RESEARCH ARTICLE

Convection heat transfer of stepped basin single slope solar still: A numerical investigation

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ABSTRACT - Solar-powered desalination is a quick and easy way to make drinking water. Numerous solar distillation systems have been investigated for various parameter modifications based on local resource availability. In this work, a solar still with a modified stepped basin is investigated to raise the rate of internal evaporation and, therefore the output yield of the solar still. Stepped basin solar stills are taken into consideration for the study since they are very effective because the water's surface exposure to radiation is greater. Thus, increasing the rate of internal water evaporation enhances the rate of convective heat transfer between the evaporating and condensing surfaces, leading to improved and consistent output. The two-dimensional stepped basin single slope solar still was investigated and contrasted with the traditional single slope still in terms of heat transfer and fluid dynamics. To optimize the configuration for better performance in various types of climatic and operational circumstances that imitate the scenario of daily life, design elements such as the number of steps and the different heights of the basin are also taken into account. Each step was added with far more success than the one before it, up until the length was reduced to 1.16% of the entire shorter length. This numerical study enables us to draw the conclusion that the rise in natural heat transfer rate with the addition of steps is mostly caused by the increased surface area and the inherently restrictive nature within the domain. Additionally, with an increase in Rayleigh number, *Ra*, the gradient variations of the traditional single slope solar still overheat transfer features have been greatly regulated and successfully raised for the modified stepped basin Solar still.

ARTICLE HISTORY

Received	:	09th Oct. 2022
Revised	:	30th Jan. 2023
Accepted	:	27th May 2023
Published	:	28th June 2023

KEYWORDS

Solar still
Stepped basin
CFD
Fluid flow
Heat transfer analysis

1.0 INTRODUCTION

Drinking water is one of the highly required components in the sustenance of life. Even though 71 % of the earth is engulfed in water, 96.5 % of which is saltwater that is unfit for drinking. Studies show that there is only 4,158,000 km^3 (9,99,000 cubic miles) of liquid drinking water available on the earth's surface. To make things even harder this amount of water is not spread evenly throughout the world. Thus, raising the need for portable drinking water. One of the most employed methods is to harvest groundwater. There are various disadvantages to this method, mainly the decrease in the water table causes a rise in pumping cost and sliding of land structures into the faults created. To overcome this, the Desalination of the major 96.5 % of saltwater is proposed. Desalination is the method of removal of salts from the given solution by evaporating and then condensing the water vapor leaving the salt solution below. Solar heat rays can be employed for this purpose. Solar still is one of the most common and simple apparatuses used just for this purpose. It consists of a trough for saltwater and an inclined surface on the top for condensation to slide off. However, this setup has low-performance value. To improve the performance of solar still, increase the rate of heat transfer involving three factors i) increase surface area ii) increase the temperature difference iii) increase the recirculation of air inside.

Various researchers have studied and reported in initial literature, to begin to understand the performance of solar still, first must go through the different types of technologies of still that are available. Murugavel et al. [1] have performed a detailed review on single basin passive type solar still which provides various methods of performance improvement by altering the orientation and structure. Torchia-Núñez et al. [2] have discussed a structured theoretical analysis of the thermodynamics behind single basin solar still including the effects of radiation, the input brine solution's physical properties and the tilt angle of the condensing along with Exergy balance. El-Agouz et al. [3] numerically tested three different models (conventional, inclined, inclined with makeup water solar still) and provided conclusive proof with a mathematical model that the inclined solar still with makeup water is 57.2% more effective than the conventional still. Abdallah et al. [4] used four thermal heat absorbing materials (black-painted basin, black-coloured metallic sponges, uncoated metallic sponges, and black-coloured rocks from north-eastern Jordan) in the solar basin and proved that they provide 28 %-43 % of performance improvement over 24 hours. Elango and Murugavel [5] introduced glass basins with varying water levels from 1cm-5cm and proved that different basin types and the water depth have considerable effects in improving the production of still. At 1 cm depth, the insulated double basin is 17.38 % higher than the single basin still

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and the un-insulated double basin is 8.12 % more than the single basin. Velmurugan et al. [6] experimentally integrated fins, area sponges and wicks at the bottom of the basin and proved that there is an increase of 29.6 % in productivity with the wicks, 15.3 % increase with sponges and 45.5 % improvement with fin. The inclusion of partitions in the bottom surface and glass cover separately was numerically analyzed by Rashidi et al. [7] to increase the Nusselt response. They concluded that the top Nusselt number is more responsive to height than to the position of the partition, and smaller vortices increase the still efficiency. To prevent heat loss and minimize shadowing effects, Srivastava et al. [8] employed porous fins made of blackened cotton rags that were partially submerged in the basin water. He concluded that there was an improvement of 56 % during the day and 48% higher when we consider 24 hours since the basin water serves as a thermal store. According to Mohammed [10], who built the novel designed stepped solar still and assessed its performance under various climatic circumstances, the solar still's enhanced efficiency varies from 40.6 % to 75 %. In an experiment, Alaudeen et al. [11] integrated an inclined flat plate collector with a stepped solar still to increase the production rate, and they compared the outcomes to those of a conventional still before and after adding sensible heat storage media. They obtained a higher evaporation rate in medium combinations with wicks and pebbles. Irfan Ali et al. [12] numerically analyzed and modeled solar still in MATLAB and studied the performance of the still by mixing water with granular activated carbon and concluded the enhancement of efficiency. S Subhani et al. [13] numerically analyzed the performance of the solar still by incorporating the baffles on the evaporating surface and by varying its position on it, hence concluded that the performance of the still is effectively improved with fewer fluctuations when the baffle is at 1/2nd position from the left wall. Although the enhanced performance of the stepped solar still is studied the rate of heat transfer and the flow structure can be further analyzed along with the comparison by adding furthermore several steps in the basin of the still. Velmurugan et al. [14] has integrated a simple single-slope solar still with sponges at the base with a mini solar pond with 80 g/kg salinity. It was proved to have a considerable increase of 27.6 % in the average production of drinking water without a solar pond. Velmurugan et al. [15] apart from introducing sponges in the basin also applied the concept of fins in the solar basin to further improve the efficiency of water production. 15 % improvement was observed with sponges, 29.6 %with wicks at the base and a drastic 45.5 % improvement with the usage of fins. Abdul Jabbar et al. [16] have provided a complete analysis of the factors that are responsible for the improvement of the solar still. They have finalized and proved that the productivity is influenced by the brine depth alone by 33 %, tilt angle by 63 %, and dye by 20 % and the radiation available. To determine the quantity of beam radiation received by any components inside the still, Feilizadeh et al. [17] created a novel radiation model in which the walls are projected onto the cover. The testing findings and the result data from this model are in good agreement, which increases the accuracy of the thermal radiation analysis of the stills performance. Rajaseenivasan et.al [18] conducted an experimental and theoretical investigation comparing the single and double-basin solar still performance with a difference of 10% in the deviation of the results. The author concluded that there is an 85 % production increase in the performance of the double basin still when compared with the single basin still. Xiong et al. [19] design and perform experimental analysis of the new multi-effect solar still with enhanced condensation surface, which decreases the condensation resistance and increases the freshwater yield. He concluded with an impressive yield of 43 kg of water in 3 days. Rahmani et al. [20] designed and tested a solar still with baffle introduced loop in natural flow movement during the summer period for 4 days. The author compared it with the dunkle's model and concluded that the air convection created has increased the maximum efficiency by 45.15 %. Rashidi et al. [21] investigated experimentally and numerically the partitioning of single-slope solar still. The author concluded that there is a steady increase in the efficiency of water production with time from 4.81 % to 8.16 % in four days compared to the conventional solar still. A good agreement between theoretical and 2D-CFD simulation for solar still was reported in the findings [22]. Subhani and Senthil Kumar [23] also reported that the change in basin shape results in an increased heat transfer rate compared to conventional basins by up to 31.4 %. Although, the previous study on solar stills has been done by enhancing their performance of it by introducing an extra baffle in it or including the solar radiation concentrators over it. According to recent research advances in the development of solar still performance, the modification of the solar still basin within the specified shape may also provide enhanced heat transfer rates and stable temperature outputs for diverse temperature situations.

The present study considered the modification of the stepped basin to the conventional solar still and analyzed the fluid dynamics and heat transfer characteristics numerically. The heat transmission aspects of the modified basin structure were compared to the standard single slope solar still, and then the varied heights of the stepped basin were researched and evaluated.

2.0 PROBLEM FORMATION

Numerical analysis of solar still was done using ANSYS Fluent after incorporating the necessary data. The model was created using space claimed and then meshed accordingly the properties of air were taken at bulk mean temperature, T_∞ i.e. $[(T_T + T_B)/2]$. In this study, the basin of the conventional single-slope solar still has been altered into the stepped basin to improve the surface area and the recirculation of air. The investigation of the modified stepped basin solar still shown in Figure 1 has factored in non-dimensional design parameters to generalize and characterize the problem more expressively with a comprehensive dynamics analysis of it. In which left side height, L_H, right side height, L_R, length of still, L_L, height of the step, h, length of step, d, top glass temperature, T_T, and lower basin temperature, T_B. The left and right walls are adiabatic and gravitational force, g acting downwards is considered. Furthermore, steps of height, h which is $L_H/10$ and length, d given by $L_L/(n+1)$ are introduced by a varying number of steps from 1 to 4. Various studies are conducted by changing the top and the bottom wall temperature ranging from 30 °C – 70 °C by keeping the difference of 10 °C and continued by changing the temperature difference from 5 °C to 25 °C.

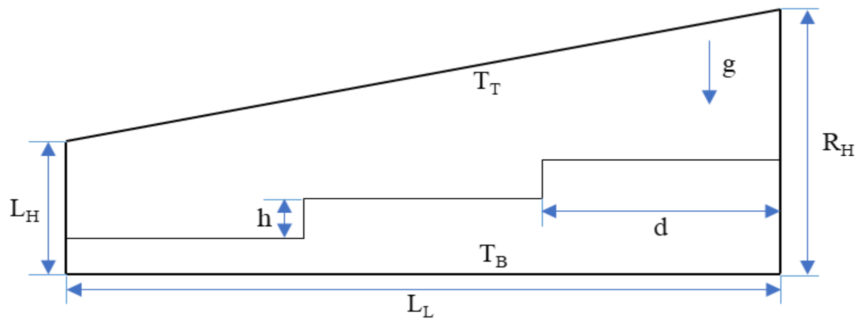


Figure 1. Single slope solar still with modified stepped basin

3.0 GOVERNING EQUATIONS, BOUNDARY CONDITIONS AND SOLUTION PROCEDURE

The following general governing equations for heat transfer and fluid flow used for 2-Dimensional applications following earlier reports [23, 24] are given after applying the necessary assumptions (Eqs. (1) to (4)) with considered pressure change, *p*, change in velocity in *x*-direction, *u* and *y*-direction, *v*, respectively. Also, the following non-dimensional equations Eqs. (5) and (6) were used to analyze the thermal characteristics of the present study.

Continuity Equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

x-Momentum Equation:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

y-Momentum Equation:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{3}$$

Energy Equation:

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+g\beta(T-T_\infty) \tag{4}$$

Rayleigh Number, *Ra*:

$$Ra=\frac{\rho.g.\beta.\ (T-T_\infty).{R_H}^3}{\mu.\alpha} \tag{5}$$

Nusselt number, *Nu*:

$$Nu=\frac{hR_H}{k} \tag{6}$$

The evaporating, T_B and condensing surfaces, T_T is maintained at constant temperature boundaries, whereas the left and right walls are adiabatic. To serve as the driving force for the transfer of heat. The fluid properties (i.e. thermal conductivity, *k*, dynamic viscosity, *μ*, thermal expansion coefficient, *β*, thermal diffusivity, *α* are assumed to be constant except density, *ρ* which is considered to be Boussinesq approximation. The equation is solved using Finite Volume Method (FVM) with necessary boundary conditions as no-slip for all walls along with adiabatic boundary for the vertical walls. The SIMPLE scheme has been implemented for pressure-velocity coupling under solution methods. The second-order upwind scheme is used for the discretization of the physical domain. Residuals preferred for converging criteria are 10^{-3} for mass and momentum and 10^{-6} for energy.

3.1 Grid Generation and Grid Independence Study

A 2-Dimensional structured mesh is preferred in this problem. As the velocity and temperature are rapidly varying near the boundaries the mesh is biased towards the edges to analyze exact flow physics and heat transfer and to avoid grid independence error a detailed study was carried out by varying the elements and finding the number of elements of 10216 has minimum influence in error by estimating the Nusselt number as illustrated in Table 1.

Table 1. Grid dependence study

Elements number	Nusselt Number, *Nu*	Variation
7984	11.95	---
9173	10.127	18.00
10216	10.00	1.27
13615	9.99	1.00

4.0 RESULTS AND DISCUSSION

4.1 Validation of the Study

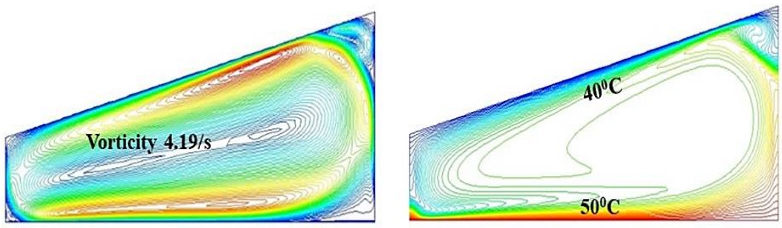
To validate the present numerical model, the performance of the solar still from the model was compared to earlier studies reported by Rashidi et al. [7] and Rahbar et al. [9], who numerically analyzed the performance of solar still with design parameters of 0.075 m on the left side, 0.187 m on the right side, and 0.438 m separation. The single-slope solar still includes an inclined condensing surface and a straight evaporation surface that is like the physical phenomena being investigated. After evaluating the fluid domain that accounts for the fluid flow and heat transfer analysis, the validation is done using the dimensions summarized in Table 2. When compared to the literature, we discovered a minimum error percentage (acceptable range) and continued for further analysis of the stated research problem.

Table 2. Validation table

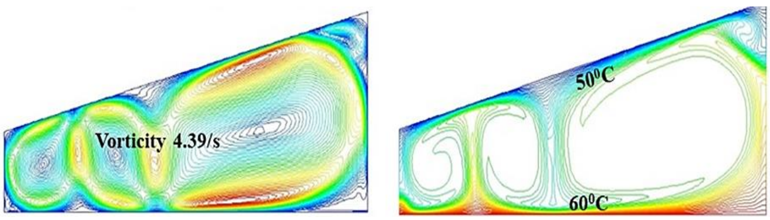
T_B (^{0}C)	T_T (^{0}C)	Nu (Rashidi et al. [7])	Nu (Rahbar et al. [9])	Nu (Present study)	Percentage of variation
63	48	10.5	10.7	10.4	2.8 % & 0.95 %

4.2 Performance Analysis of Stepped Basin Modified Still under Constant Temperature Variation of 10°C

The current investigation started with a comparison of the temperature and velocity contours of a solar still with a single slope using varied evaporating surfaces at a constant temperature difference. The Ansys-Workbench setup was used for post-processing (assessment of flow and heat transfer characteristics), and velocity and vorticity contours were constructed to analyze the flow structure and thermal characteristically behavior. The analysis is progressed by modifying the basin of single slope solar still to increase the effective surface area and confining the flow. When the still is condensing and evaporating surface is at 30 °C and 40 °C respectively, the non-uniform multiple vortices whose magnitude decreases when compared to the conventional still (see Figure 2) along with an increase in heat transfer rate at both base and step collectively. Increase the condensing and evaporating surface temperatures by 10 °C of the stepped basin solar still; it is observed (see Figure 3) the same nature of multiple vorticity patterns as before but with reduced velocity and vorticity magnitude with a significant increase in heat transfer rate when compared to conventional still. Again, when the temperature of the condensing surface (50 °C and 60 °C) and evaporating surface (60 °C and 70 °C) increases, there is no change in the vorticity pattern with decreasing velocity and vorticity magnitude but a large rise in convective heat transfer rate (Table 3). When a conventional still is built with a baffle inside the flow domain, this behavior is analogous to the formation of a flow structure [13]. This is because the unicellular vortex production bifurcates in the classic single slope solar still with lesser vorticity magnitude given by the flow development's abrupt step edge. A similar trend may also be seen in the higher *Ra* number regime.

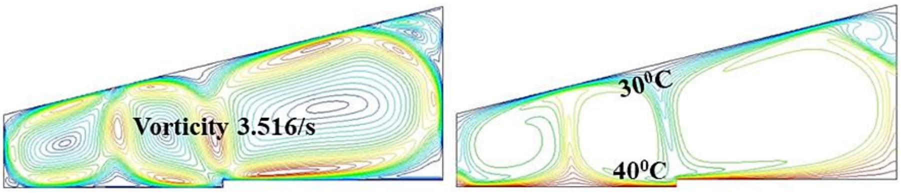


(a) Velocity contour (0.049 m/s) Temperature contour

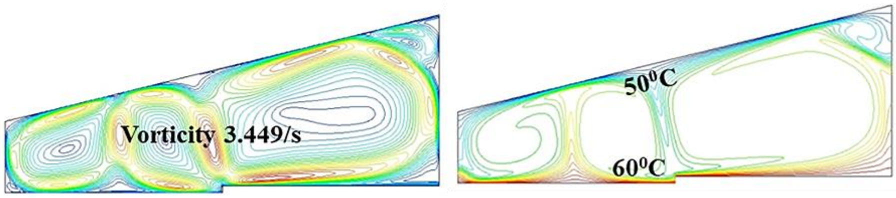


(b) Velocity contour (0.05 m/s) Temperature contour

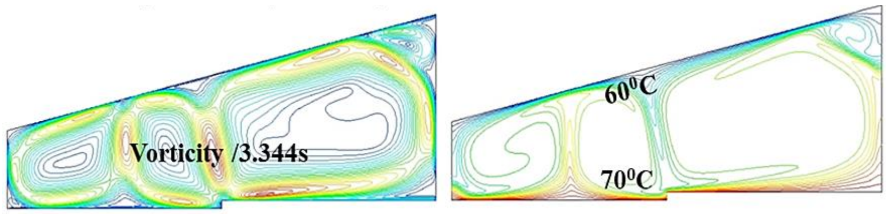
Figure 2. Velocity and temperature contours of conventional still under constant temperature difference



(a) Velocity contour (0.05 m/s) Temperature contour

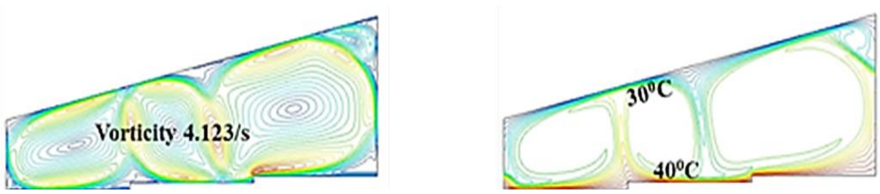


(b) Velocity contour (0.046 m/s) Temperature contour

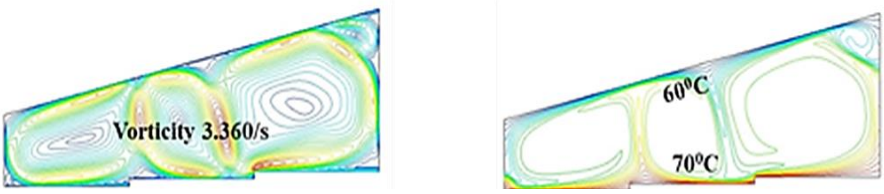


(c) Velocity contour (0.041 m/s) Temperature contour

Figure 3. Velocity and temperature contours of single stepped solar still under constant temperature difference



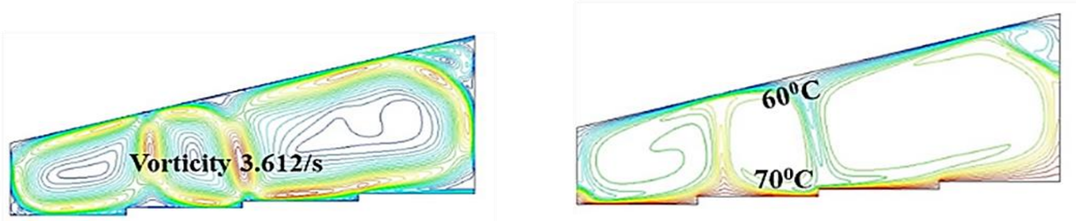
(a) Velocity contour (0.047 m/s) Temperature contour



(b) Velocity contour (0.052 m/s) Temperature contour

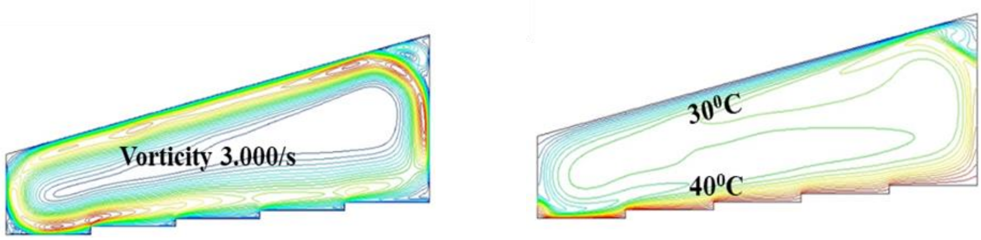
Figure 4. Velocity and temperature contours of two stepped solar still under constant temperature difference

Now the design has been further modified by increasing the steps as the productivity of a single step has increased when compared with the standard single slope solar still. In two stepped still when the temperatures of evaporating and condensing surfaces are 30 °C and 40 °C respectively we can observe that in the base step, the changes are minimal but there is a significant doubling effect in the rate of heat transfer at the first step than other. When comparing the two-stepped solar still with the conventional solar still it proves to be highly effective in productivity (see Table 3). The flow structure development and vorticity magnitude are both affected by the dual bifurcation effect. Similarly, the channel given for the fluid to circulate within has been limited to distinct regions as seen in Figure 4, allowing the fluid to receive more heat from the evaporating surface than in a single-step case. But when increasing the agitation by maintaining the constant temperature difference, the heat transfer rate nearer to the base is increasing along with the highest step but the middle step of the still is decreasing as shown in Figure 5. When comparing three-stepped solar stills to traditional solar stills, it is noticed that there is a significant increase in heat transmission rate. When the temperatures of the evaporating and condensing surfaces are raised, there is a steady rise in convective heat transfer between the base and top steps, with a reduction near the first and second steps (see Figure 5). When compared to the two-stepped solar still, it can see in Table 3 that the heat transmission rate has also grown tremendously.

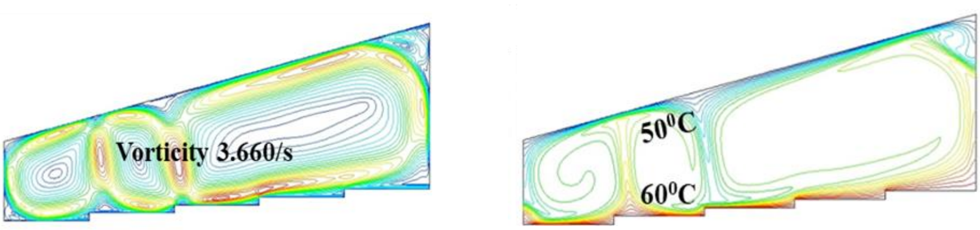


Velocity contour (0.05 m/s) Temperature contour

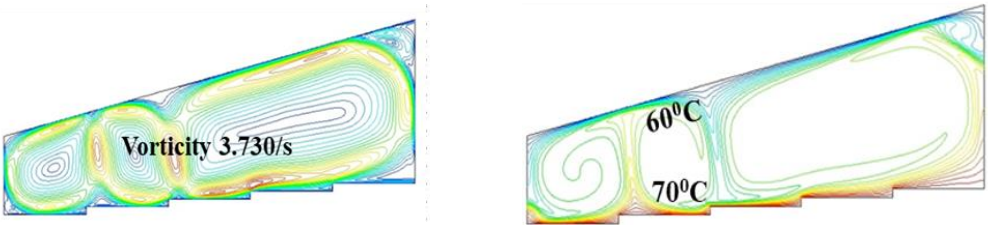
Figure 5. Velocity and temperature contours of three stepped solar still under constant temperature difference



(a) Velocity contour (0.032 m/s) Temperature contour



(b) Velocity contour (0.044 m/s) Temperature contour



(c) Velocity contour (0.047 m/s) Temperature contour

Figure 6. Velocity and temperature contours of four stepped solar still under constant temperature difference

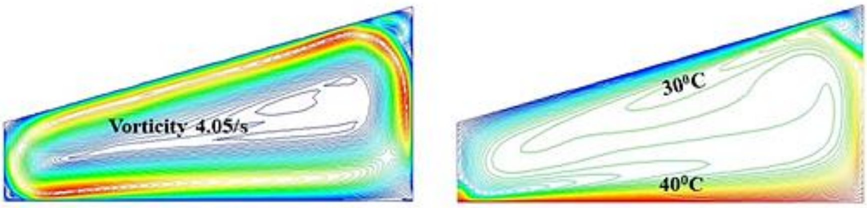
Table 3. Nusselt number at constant temperature difference for with and without steps in the basin

Bottom wall temperature (°C)	Nusselt number, *Nu*				
	No step (Conventional)	Single Stepped	Two Stepped	Three stepped	Four stepped
40	9.36	12.68	14.05	14.16	9.93
50	9.36	12.58	14.05	14.15	14.82
60	12.17	12.60	14.13	14.06	13.85
70	12.17	12.51	14.10	14.06	15.79

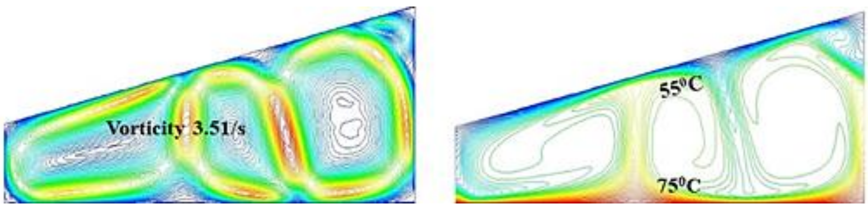
A Bi-circular vortex with the axis normal to the condensing surface is observed at the lowest temperatures of the condensing surface of 30 °C and the evaporating surface of 40 °C. This is owing to the fluid's boundary layer formulation across the step margins, and as a result, the fluid is not accessible to the step edge surface for effective heat transmission. Thus, the effective thermal energy transfer has also degraded as the vortices produced inside of it have diminished. Even though after increasing the temperature influence inside the domain, the creation of four tiny vortices as the temperature rises can still been seen as shown in Figure 6. When compared to conventional solar still, the maximum value of convective heat transfer of the modified solar still is observed (see Table 3). When the temperature of the condensing and evaporating surfaces is agitated, the heat transfer value fluctuates greatly.

4.3 Performance Analysis of Stepped Basin Modified Still under Variable Temperature Differences

Additionally, when the difference in temperature between the evaporating and condensing surfaces ranges from 5 °C to 25°C with a 5°C rise. This temperature differential is applied to a standard solar still, the rate of convective heat transfer changes (see Figure 7). As seen in Figure 11, the lowest heat transmission is reached at 10 °C and the maximum at 15 °C temperature differential when the massive vortex splits into smaller vortices, speeding up the rate of heat transfer. The temperature difference between the surfaces that are condensing (25 °C), and evaporating (30 °C) is now 5 °C in the modified stepped basin (one step). As shown in Figure 8, it does not seem like the different vorticity patterns have altered. A temperature difference of 5 °C makes the single step more efficient than a 10 °C temperature difference makes the normal solar still. Even though the study's flow region is narrower in this instance, more vorticity is formed than in conventional solar still. As a result, the modified stepped basin solar still outperforms the standard single-slope solar in terms of heat transmission. When there is a divergence of the flow pattern produced previously [24, 25], the vortices formed with increased velocity aid in more heat transfer and boost the performance of the solar still. By increasing the temperature difference between the evaporating and condensing surfaces from 5 °C to 25 °C, a gradual decrease in the rate of convective heat transfer near the base plate and a constant increase near the first step as the magnitude of vorticity increases with the same non-uniform vortices is observed as shown in Figure 11.

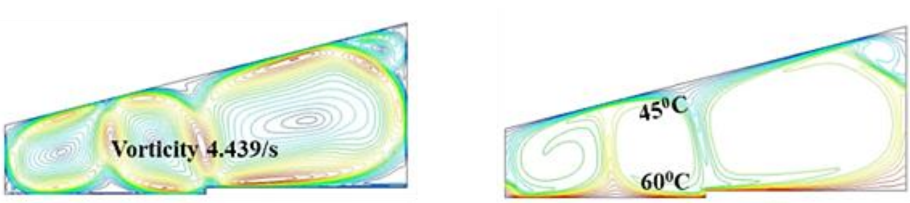


(a) Velocity contour (0.038 m/s) Temperature contour

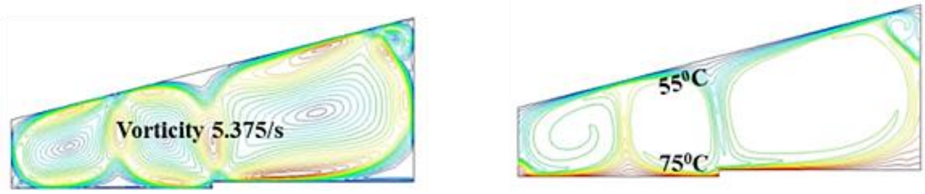


(b) Velocity contour (0.035 m/s) Temperature contour

Figure 7. Velocity and temperature contours of conventional still under variable temperature difference



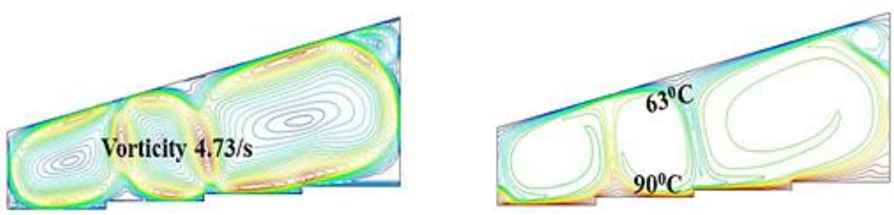
(a) Velocity contour (0.047 m/s) Temperature contour



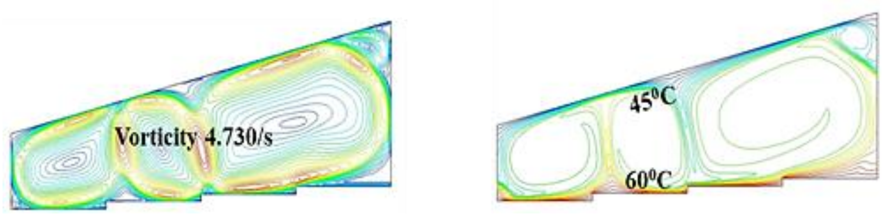
(b) Velocity contour (0.04 m/s) Temperature contour

Figure 8. Velocity and temperature contours of single stepped solar still under variable temperature difference

It is discovered that the rate of heat transfer rises in comparison to the traditional solar still as the variable temperature is applied in the boundary conditions of a two-stepped solar still. Up until a temperature difference of 20 °C, where the rate of heat transfer increases closer to the base and the highest step but drops in the intermediate step, there is a steady increase in vorticity and reduction in velocity. As shown in Figure 11, there is a reduction in the rate of heat transfer when the magnitude of the vorticity and velocity drops, leading to reduced rate of heat transfer, at the temperature difference of 25 °C between the condensing (63 °C) and evaporation (90 °C). The magnitude of the vorticity increases in tiny values between 5°C and 25°C when the temperature fluctuations are applied in the three-stepped solar still. The magnitude of velocity is also growing at extremely low levels, as seen by the velocity contours in Figure 9. With the continual agitation of temperature differences between the evaporating and condensing surfaces, the rate of heat transfer near all the stages rises. This behavior also contributes to the development of heat transfer characteristics and the knowledge of flow structure enhancement for better heat transfer ability for solar still applications [9].

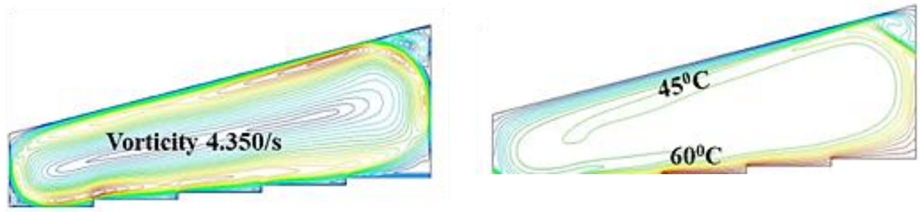


(a) Velocity contour (0.06 m/s) Temperature contour

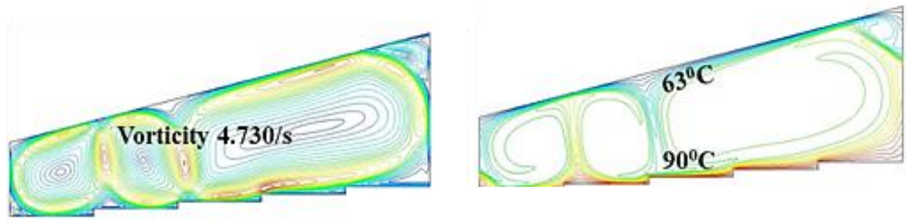


(b) Velocity contour (0.06 m/s) Temperature contour

Figure 9. Velocity and temperature contours of three stepped solar still under variable temperature difference



(a) Velocity contour (0.058 m/s) Temperature contour



(b) Velocity contour (0.059 m/s) Temperature contour

Figure 10. Velocity and temperature contours of four stepped solar still under variable temperature difference

Upon the temperature differences in four stepped solar still, the velocity contours consist of various multiple vortices structures. Additionally, varying the magnitudes of the vorticity and velocity (see Figure 11), agitates the temperature difference between the evaporating and condensing surfaces. This leads to the heat transfer rate fluctuating at random as shown in Figure 10. Additionally, the heat transfer mechanism observation shows that the *Nu* over *Ra* increment fluctuations has been significantly minimized and that the heat transfer ability is increasing linearly with *Ra*. The creation of a boundary layer over the supplied step edges and the increasing amplitude of the vortices' velocities inside the domain are the key causes of this. Although there are fluctuations in the convective heat transfer rate, the maximum is reached when there is a 20 °C temperature differential between the condensing surface (75°C) and the evaporating surface (55 °C). This shows that the fluid efficiently participates in the rate of heat transfer at the specified agitated condition and step. The preceding chart in Figure 11, notably around 3100×10^3, shows that there is a drastic shift in the no-step and four-step Nusselt numbers regarding the *Ra*. It is due to unforeseen performance spikes are brought on by the unequal rate of convective heat transfer.

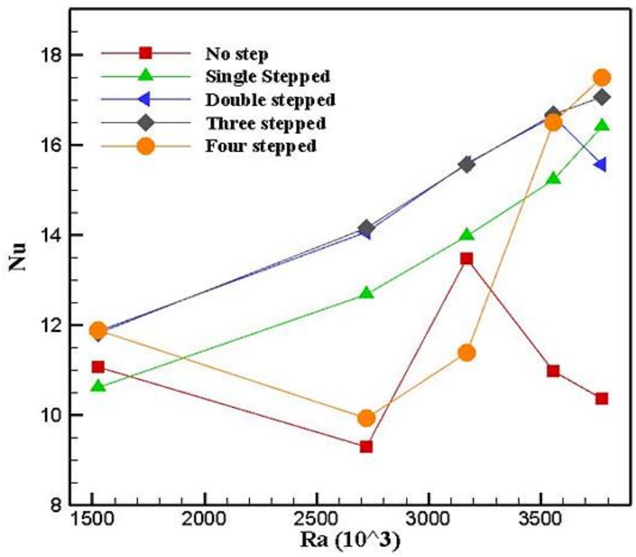


Figure 11. Nu vs Ra plot when the still is at variable temperature difference

5.0 CONCLUSION

The characteristic heat transfer and flow pattern are analyzed for stepped single basin solar still with constant and varying temperature differences between the evaporating and condensing surfaces. Comparing these values with the standard solar still (see Figure 11 and Table 3), there is a significant improvement in the performance of solar still. The stepped still at a lower temperature difference has higher heat transfer than the standard solar still at the same temperature and summarized the prospects below:

1) This enhancement is mainly because of the improvement in the convective heat transfer caused by the increased surface area due to adding the steps and the breaking of large vortex into smaller vortices without lowering the magnitude of vorticity.
2) The addition of each step proved to be much more effective than the previous one till the length of the step was reduced to 1.16% of length of still, L_L. The rate of heat transfer at 1.16% of length of still, L_L is more agitated because the magnitude of velocity increases with a decrease in the vorticity at various temperature variations indicating the uneven rate of convective heat transfer.
3) This numerical investigation allows us to conclude that the increase in natural heat transfer rate with the addition of steps is mostly due to the increased surface area and the given arresting character.
4) To increase the effectiveness of the suggested model, sponges and dark dye might be used. To investigate convective heat transport, this device can be modified to incorporate a curved cover top and baffle.

6.0 ACKNOWLEDGMENTS

The authors gratefully acknowledge the computer and modeling resources offered by the mechanical engineering department, Product Development (PD) lab and CFD lab at SRM Institute of Science and Technology.

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