Application of Software in Predicting Thermal Behaviours of Solar Stills

Anirshu DevRoy, Om Prakash, Shobhana Singh and Anil Kumar

Abstract Software plays a major role in analysis and simulation of solar stills. These simulation techniques are very much cheaper and time saving compared to the experimental analysis of a system. This chapter explains the different software used for the design and testing of various models of solar still. It also gives an overall idea of what type of software being used and its feasibility. Software like MATLAB, ANSYS and FLUENT have been taken into account here for modelling and development of various solar stills. Moreover, software such as SPSS is often used for statistical data analysis. All recent software have been selected and reviewed and the benefits explained.

Keywords Solar still · Simulation · Modelling · CFD · FORTRAN · MATLAB · SPSS

Nomenclature

A	Area, m^2
A_g	Aspect ratio for glass $A = L/H$
C	Vapour concentration of air, kg m^{-3}
c	Specific heat, J kg^{-1} $°C^{-1}$
C_p	Specific heat capacity at constant pressure, J kg^{-1} K^{-1}

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C_{wg}	Specific heat of water and glass cover, J kg^{-1} °C^{-1}
D	Depth of water, cm
D_{ag}	Diffusion coefficient of gas phase
d_w	Depth of saline water, m
F	Solar radiation absorption factor, dimensionless
G	Irradiance, W m^{-2}
g	Solar flux
Gn	Grashoff's number
H	Solar irradiation, kWh/m^2
h	Convection heat transfer coefficient, W m^{-2} K^{-1}
h_{glc}	Heat transfer coefficient of glass cover, W/m^2 K
h_p	Convective radiative heat transfer coefficient from outer glass surface cover to ambient, W/m^2 K
I_t	Tilt of incident solar radiation, W m^{-2}
$I_s(t)$	Solar radiation over the solar still glass cover, W/m^2
K	Thermal conductivity
Le	Lewis number
L_v	Latent heat of vaporization, J/kg
$\dot{m}$	Specific mass, kg/m^2
m'_b	Mass rate of brine, kg m^{-3}
m'_{ev}	Produced mass rate of vapour, kg m^{-3}
m_{eva}	Mass for evaporation, kg
m_{evap}	Rate of mass evaporation, m/s
M_{gl}	Interphase momentum transfer, kg/m^2 s^2
m_{lg}	Rate of interphase mass transfer, kg/m^3
m'_{sw}	Mass rate for saline water, kg m^{-3}
$\dot{m}_{wg}$	Mass flow rate of water and glass cover, kg s^{-1}
P	Pressure, N/m^2
P_{ci}	Partial saturated vapour pressure at condensing cover temperature
P_d	Calculated daily productivity, 1/m^2 day
Pr	Prandtl number
P_v	Partial saturated vapour pressure at water temperature
$\dot{Q}$	Heat transfer rate, W
q_a	Convective heat transfer, W
$q_{e,v}$	Heat transfer per unit area per unit time
Q_{lg}	Energy transfer between liquid and gas phases
R	Ratio of evaporator chamber volume to condenser chamber volume, dimensionless
r	Volume fraction, dimensionless
Rd	Radius of tubular solar still, m
Sc	Schmidt number
T	Temperature, °C
t	Thickness, m
t_a	Average ambient temperature, °C
T_{am}	Temperature ambient, °C

T_g Glass temperature, °C
T_{gin} Inner glass surface temperature, °C
T_{gout} Outer glass cover temperature, °C
T_v Water temperature, °C
U Side heat loss coefficient from basin to ambient, W m^{-2} K^{-1}
u X component of velocity, m s^{-1}
U_{eva} Heat transfer coefficient for evaporation, W/m^2 K
V Velocity vector, m/s
v Y component of velocity, m s^{-1}
W Wind velocity, m/s
w Compressor power, w
X_A Mass fraction of liquid phase
Y_A Mass fraction of gas phase
y_b Concentration of salt in brine, mg l^{-1}
y_{sw} Concentration of salts in feeding water, mg l^{-1}

Greek Symbols

β Reflectivity
γ Thermal diffusivity of air, m^2 s^{-1}
λ/φ Brine depth to frontal height, –
φ_g Latitude of glass cover, °
φ_w Latitude of water, °
ϕ Glass inclination angle, °
ρ Density, kg/m^3
σ Stefan–Boltzmann constant (5.67×10^{-8} W m^2 K^{-4})
μ Viscosity, kg/m s
χ Feed concentration factor

Subscripts

1 Initial
a Air
B Base
b Direct beam of solar radiation
Bs Basin
c Convective
e Evaporative
eff Effective
ev Evaporator

f	Refrigeration
g	Glass
l	Side loss
Liq	Liquid
rad	Radiative
v	Water

1 Introduction

The harnessing of solar energy began in 1839 when Alexandre Edmond Becquerel discovered that certain materials produce small amount of electric current when exposed to light [1]. Henceforth, solar energy is being used in some productive manner other than natural use. Now in the twenty-first century with drastic increase in human population, the non-renewable energy resources are being exhausted at very high rate. The demand for renewable energy has increased, and this leads to massive development in alternative energy sources like solar, wind, water, geothermal. New designs and developments are being done causing lesser pollution and at low cost with high efficiency.

Altogether, serious steps are being taken for conserving the natural habitat. Now natural habitat is composed of soil, air, water, etc. Considering water, although the world has abundance of water, fresh water is of only 2% of the world's water supply. In recent times, with the increase in population, fresh water in the world is decreasing at an alarming rate, which leads to alternative methods for extracting fresh water [2]. One of them is the usage of solar still to extract fresh water from impure water. Solar still is having its use since the pre-Incaian period. After that, various types of designs and modifications have been suggested and implemented. The solar still distils water using the heat of the sun to evaporate and then cool and collect it. The application of solar still is not just extraction of pure distilled water but to provide fresh water in regions where the freshwater availability is not easy. Using solar still, fresh water can be obtained easily at a low cost, but like all other conventional devices, it is quite time-consuming. However, the fresh water finally available is in a very low quantity. Various modifications in design are made to increase the usability of the solar still based on different categories to enhance its productivity. Some of the methods to increase the productivity of a solar still are to change its shape or the materials used which absorb large amount of heat energy, using the optimum angle of inclination, etc. [3].

Figure 1 illustrates the basic design of a solar still; here, the contaminated water lies at the bottom of the container, and due to solar radiation, water gets evaporated and condensed water droplets are formed on the upper glass cover which is finally collected as fresh water. Now each category of solar still has various types of design based on its shape and size. Each produces a different amount of fresh water and has various merits and demerits. All these types are experimented individually, and the data are used by various researchers and manufacturers across the globe. Now an experimental investigation of such stills are quite time-consuming and hectic, and the problem of human error comes into existence which can disturb the main reading; to avoid such circumstances, software applications are used to predict the desired outcome by simulating similar environment saving time and energy. Software application also has the benefit of taking in large and variety of data providing intricate details of the experiment and the possibilities for developments. This software provides us with the details of water productivity, efficiency, heat transfer rate, ambient solar radiation temperature, etc. Computational fluid dynamics (CFD) can be used to predict the possibilities and the extent of experimental results of a still, such as finding out the heat transfer coefficient, experimental determination of productivity of a still, temperature distribution pattern, through simulations using various governing equations such as the heat and mass transfer equations, energy and momentum equations of various solid and liquid phases. 2D and 3D CFD simulations are done; in both the cases, the results obtained are close to accurate, where few precision is lost in case of 2D simulation. MATLAB is used for mathematical modelling and for comparing the results obtained with the experimental results. For statistical data analysis, SPSS is also used for the performance evaluation of various types of solar stills. FORTRAN programming is also used by various researchers to evaluate parameters [4].

The aim of the chapter is to provide a detailed description of various software applications used for the solar still research. Each chapter provides all the details about which software is used for simulation. A better insight on software to conduct a solar still research is provided through this. Research conducted by other researchers is taken into account. The content shall provide with which software is better to use and has been proven useful for solar still based on its category. Such a collection of complete analysis of software used and its use is not available till now as a whole. Hence, the main challenge of this chapter is to present a comprehensive feedback of analysis and performance of software application in various types of stills based to their categories. This chapter will help any scientist, manufacturer or researcher to get an overall idea of the software to be used for their research on any type of still.

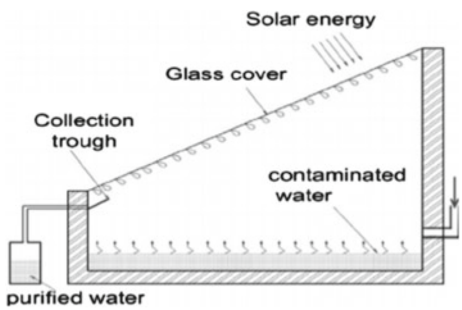


Fig. 1 Schematic diagram of a single-basin solar still [43]

2 Simulation Methodologies

Due to recent developments in software and various data collection of the performance of the solar stills, there has become numerous methods which can be used to predict the outcome of a still. These outcomes can be called simulations, and the various techniques for finding out the result of the outcome are called simulation methodologies. Now for conducting a simulation, there are various types of solar stills [4]. They can be classified on the basis of effect such as single-effect and multi-effect stills, which are further classified as active and passive stills depending upon the source of heat used to evaporate water either directly through sun or through any external aid. The figures below show the basic diagram of single- and multistage solar stills (Figs. 2 and 3).

2.1 CFD Simulation

In the end of twenties, the use of CFD for finding the final results of a solar still was in practice under no wind conditions [5]. The simulations were done using TASC flow. It is based on finite volume analysis of CFD simulation. Since it did not consider one of the parameters, wind flow, the results were restricted to a certain domain.

CFD study was used to find out the film coefficient of a single-slope solar still (SSS) [6]. The study had good correlation with the previously well-acquainted mod-

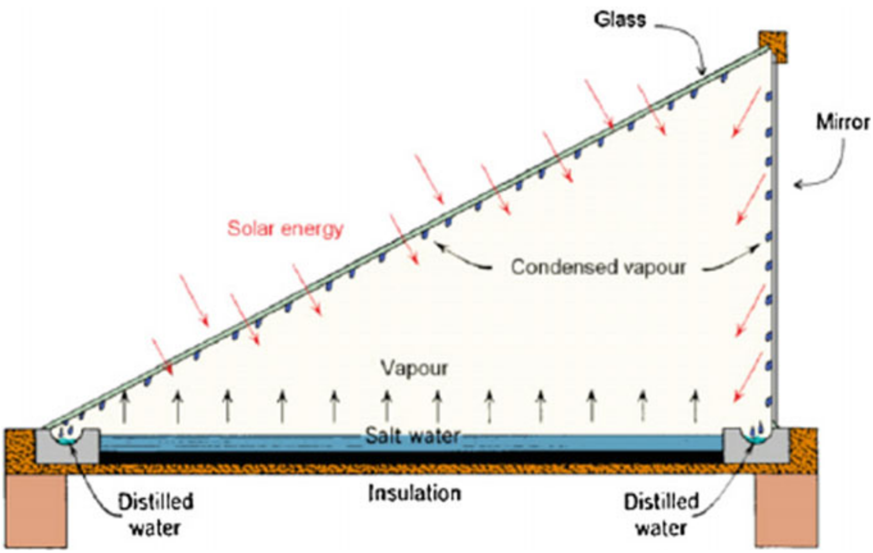


Fig. 2 Single-stage solar still [44]

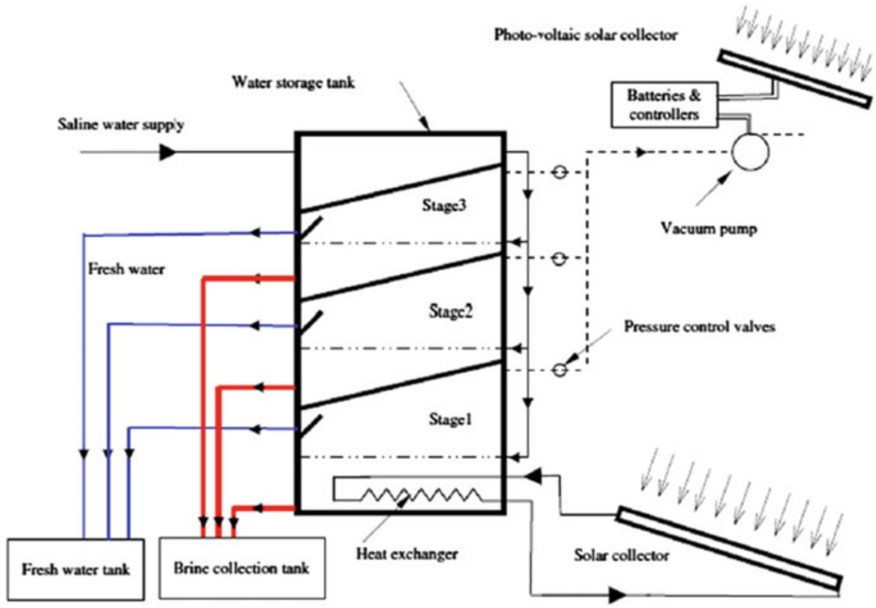


Fig. 3 Multistage solar still [45]

els. The motive of the study was to find out the free convection effect in 2D single SSS. The CFD simulation had a governing equation based on a numerical model.

The numerical model was made based on the SIMPLEC algorithm. Equation (1) illustrates heat transfer equation due to convection between water and glass. It is one of the main governing equations:

$$q_a = h_{a,v-g} A_g \left(T_v - T_g\right). \quad (1)$$

Here $h_{a,v-g}$ is the convection heat transfer coefficient. It is not a property rather it is an experimentally determined parameter that depends on the values of the variables affecting the still geometry. A_g is the area of the surface where the convection heat transfer phenomenon takes place, and T_v, T_g is the temperature of the water and the top glass cover. Altogether, a less emphasis was given to CFD. The conclusion was made that the film coefficient was maximum in the area of the glass where air moves towards the water surface, which is downward.

A flat plate solar still was analysed using CFD. In the simulation, a 3D temperature pattern of the still was studied. Finally, the experimental results were correlated with the simulation results, and it has good coexistence.

The effects of blade installation were studied for the analysis of heat transfer coefficient and flow of fluid [7]. The study was carried out using CFD FLUENT software using SIMPLEC algorithm. The flow of fluid was assumed to be steady

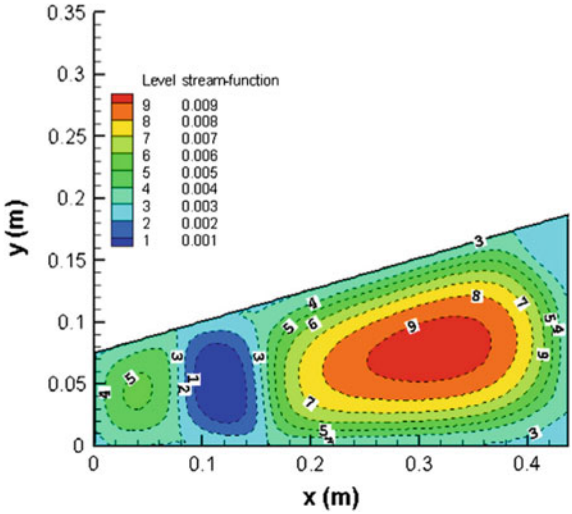


Fig. 4 The non-bladed still contour of the stream [7]

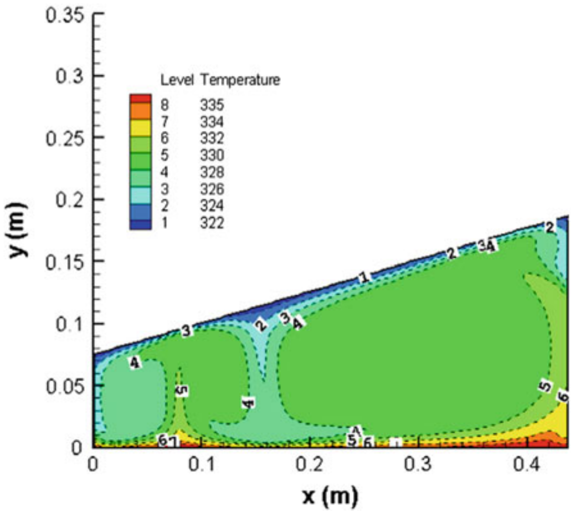


Fig. 5 Non-blade still constant temperature plots [7]

and 2D and laminar flow. The following figures show that the CFD simulations have taken place.

Figures 4 and 5 show the temperature changes and the stream functions plot. From the figures, it can be seen that there are 3 vortices. The left one and the right one rotate in anticlockwise direction and the middle one rotates in clockwise direction. These vortices start from the bottom and continue till the glass. These occurrences describe the process of heat interchange and the natural convection. Figures 6 and 7 illustrate the temperature changes and the stream function of a bladed still. The blade increases the number of vortices and hence increases the process of heat transfer.

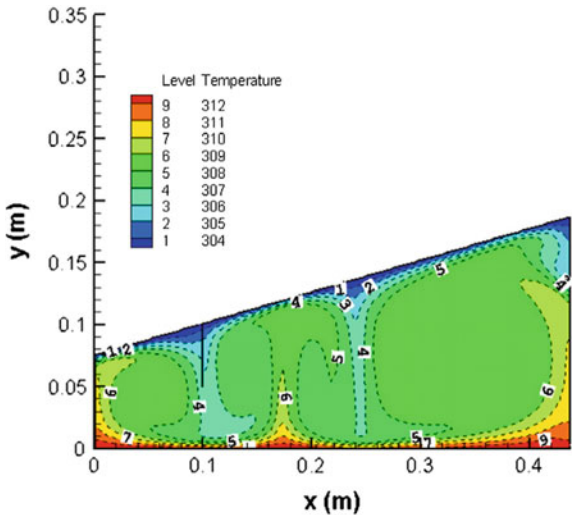


Fig. 6 Bladed still constant temperature plot [7]

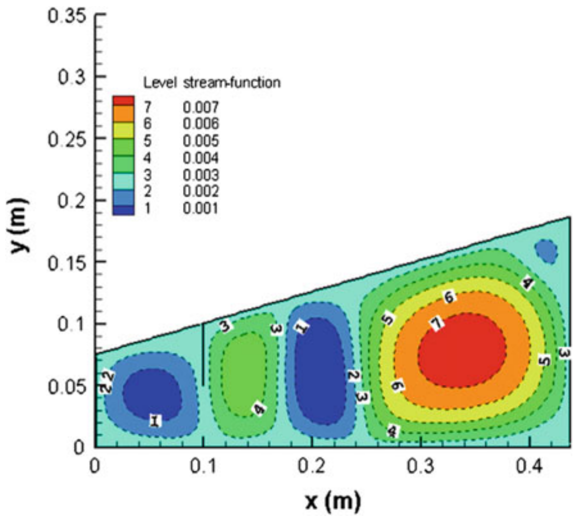


Fig. 7 Bladed still contour of stream [7]

Figures 8, 9 and 10 illustrate the effect of the vortices due to inappropriate blade installations. All these lead to decrease in the rate of heat transfer, which results in the decrease in the amount of fresh water obtained. Finally, the result obtained was that one blade had increased the efficiency but more than one decreased the efficiency.

A study on the modelling of a still was done to increase the efficiency of the design parameter [8]. It was 3D model of the two phases, i.e. liquid and gas, for evaporation and condensation processes. CFD was used to simulate the model.

Equations (2)–(11) illustrate few of the governing equations used in the CFD modelling:

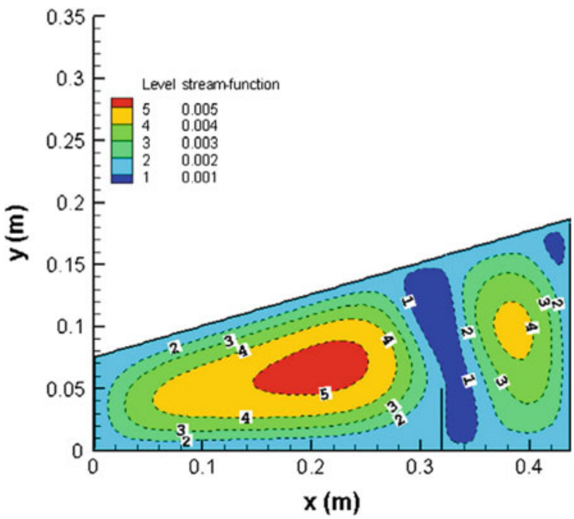


Fig. 8 Displacement of large vortex due to blade [7]

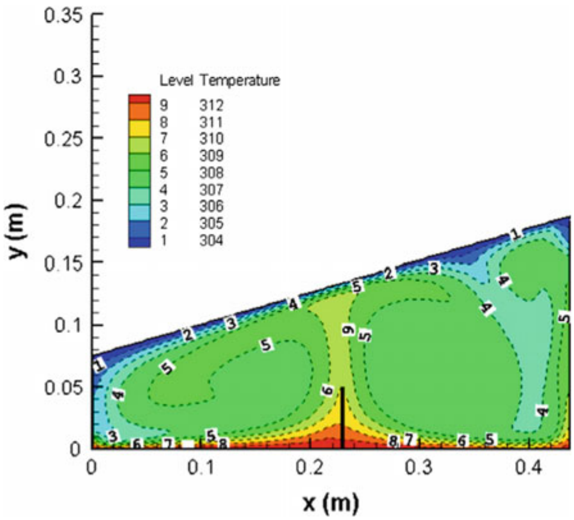


Fig. 9 Improper blade installation on the boundary [7]

Continuity Equations:

$$\text{Gas phase} - \nabla \cdot \left(r_{\text{gas}} \rho_{\text{gas}} V_{\text{gas}}\right) - m_{\text{lg}} = 0 \tag{2}$$

$$\text{Liquid phase} - \nabla \cdot \left(r_{\text{liq}} \rho_{\text{liq}} V_{\text{liq}}\right) - m_{\text{lg}} = 0 \tag{3}$$

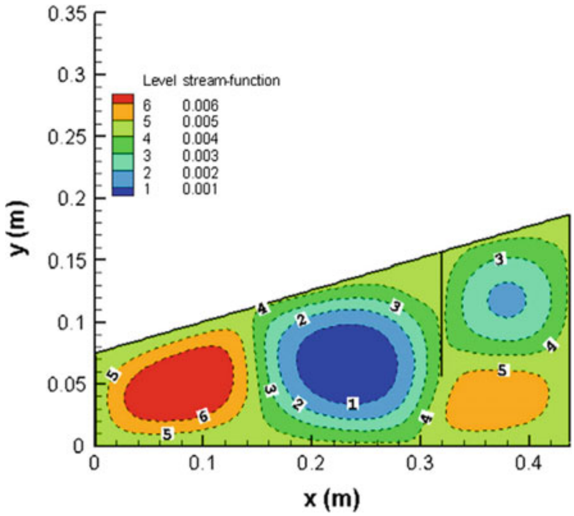


Fig. 10 Resistance of the vortices due to improper installation of the blade [7]

m_{lg} is the mass transfer rate from liquid state to gaseous state. The mass transfer must satisfy a balancing equation of $m_{lg} = -m_{gl}$.

Momentum Equations:
Gas phase

$$\begin{aligned}&\nabla \cdot \left(r_{gas}\left(\rho_{gas} V_{gas} V_{gas}\right)\right)\\&= -r_{gas}\nabla P_{gas} + \nabla \cdot \left(r_{gas}\mu_{laminar,gas}\left(\nabla V_{gas} + \left(\nabla V_{gas} + \left(\nabla V_{gas}\right)^T\right)\right)\right)\\&\quad + r_{gas}\rho_{gas} g - M_{gl}\end{aligned} \tag{4}$$

Liquid phase

$$\begin{aligned}\nabla \cdot \left(r_{liq}\left(\rho_{liq} V_{liq} V_{liq}\right)\right) = -r_{liq}\nabla P_{liq} + \nabla \cdot \left(r_{liq}\mu_{laminar,liq}\left(\nabla V_{liq} + \left(\nabla V_{liq}\right)^T\right)\right)\\ + r_{liq}\rho_{liq} g + M_{gl}\end{aligned} \tag{5}$$

M_{gl} is the force acting on the boundary region due to the presence of other phases.

Energy equations of gas and liquid phases:

$$\nabla \cdot \left(r_{gas}\rho_{gas} V_{gas} h_{gas}\right) = -\nabla \cdot q + \left(Q_{lg} + m_{lg} h_{lg}\right) \tag{6}$$

$$\nabla \cdot \left(r_{liq}\rho_{liq} V_{liq} h_{liq}\right) = -\nabla \cdot q + \left(Q_{lq} + m_{lg} h_{lg}\right) \tag{7}$$

Here, h_{liq}, h_{gas} are enthalpies of the liquid and gas phases.

Volume Conservation Equation:

$$r_{\mathrm{gas}} + r_{\mathrm{liq}} = 1 \tag{8}$$

Pressure Equations:

$$P_{\mathrm{gas}} = P_{\mathrm{liq}} = P \tag{9}$$

Mass Transfer Equation:
Gas phase

$$\nabla \cdot \left[r_{\mathrm{gas}} \left(\rho_{\mathrm{gas}} V_{gas} Y_{\mathrm{a}} - \rho_{\mathrm{gas}} D_{\mathrm{ag}} (\nabla Y_{\mathrm{a}}) \right) \right] - S_{\mathrm{lg}} = 0 \tag{10}$$

Liquid phase

$$\nabla \cdot \left[r_{\mathrm{liq}} \left(\rho_{\mathrm{liq}} V_{\mathrm{liq}} X_{\mathrm{a}} - \rho_{\mathrm{liq}} D_{\mathrm{ag}} (\nabla X_{\mathrm{a}}) \right) \right] + S_{\mathrm{lg}} = 0 \tag{11}$$

ANSYS CFX 11 was used for carrying out the simulation. The time for each simulation was around 4–12 h based on the condition of the computer. The basic structure development was done in ANSYS workbench 11. The model was more or less tetrahedral in shape. The simulation results were checked by increasing the grid size of the mesh. The greater the increase in grid cells more was the simulation closer to the real model results. The rate of final water and the temperature of water were obtained from the simulation. The following diagram illustrates the analysis of behaviour of the liquid and gas during simulation of the still and gives a detailed explanation followed by it.

Figure 11 illustrates the condensation of water on the inclined glass cover. As can be seen, the bottom part has the maximum volume of water accumulated, whereas the least volume of water is in top most area.

Figure 12 illustrates the water and gas interaction on the glass cover in the bottom corner. As can be seen that water in the form of liquid stays at the bottom most point and rest is acquired by water vapour.

From Fig. 13, a uniform temperature distribution present on the vertical axis can be seen (Fig. 14).

Similar to the temperature distribution, a volume distribution diagram obtained shows that the entire vertical portion was covered by gas mixture and only the bottom most and the corner part was occupied by the liquid phase.

Figure 15 gives the velocity of gas at various points on the still. The upper region is the warm gas which rises due to increase in temperature, whereas the lower part is the cooler gas; hence, from the diagram, a heat transfer taking place due to convection can be seen. The usage of new film coefficient resulted in more accuracy in the

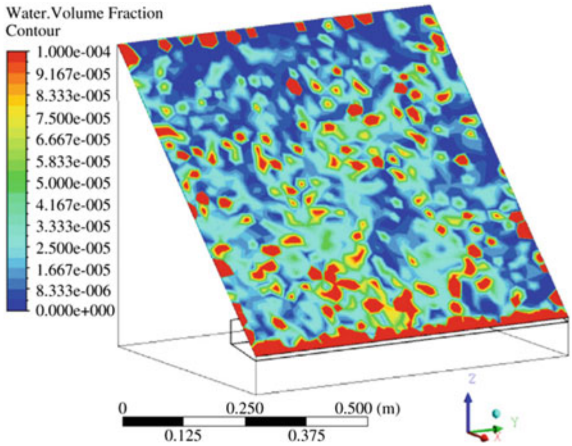


Fig. 11 Amount of water accumulated on the glass of the still [8]

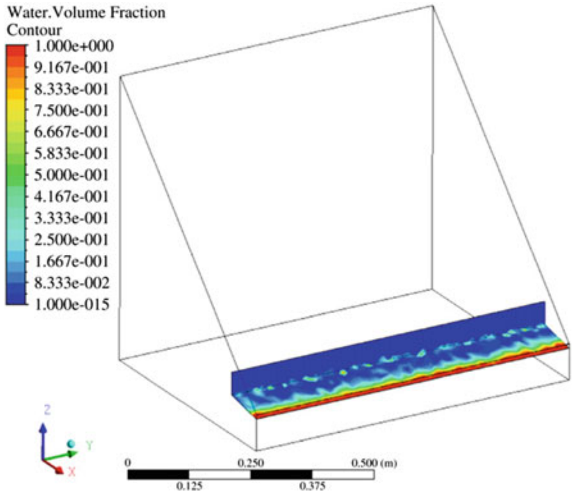


Fig. 12 Water accumulated at the bottom of the still [8]

simulation results in comparison with the experimental results. Moreover, it affected only the water temperature and not the production of fresh water. The Nusselt number was calculated for the still. Finally, using this equation $Nu = C(Gr \cdot \mathrm{Pr})^n$, C and n values from the CFD model were found to be 2.054 and 1.66, where Gr and Pr are the Grashof number and Prandtl number. Thus, CFD is a useful software for making new designs based on parameters. Modifications can be made on the solar still using CFD by comparing the parameters to the experimentally obtained values.

The 2D simulation was done for a tubular solar still (TBSS) for estimating the coefficient of heat and mass transfer and for the determination of water productivity [9]. The software used was ANSYS-FLUENT 14.0 for simulating the flow pattern. A first-order upwind scheme is used for convection and diffusion. The effects due to pressure and velocity were taken care by the SIMPLEC algorithm. The solutions

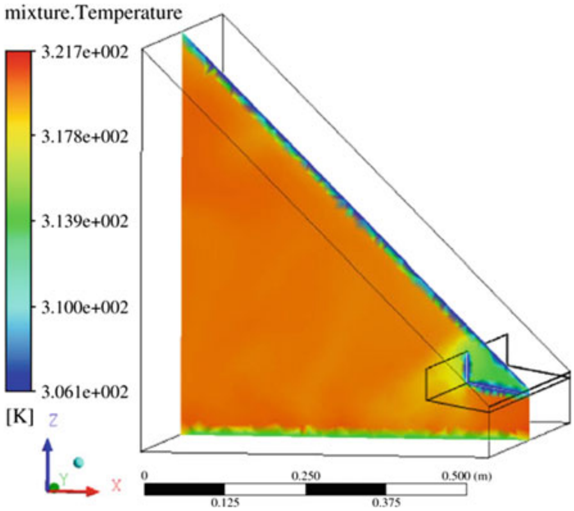


Fig. 13 Temperature of mixture of gases occupied on *y* axis [8]

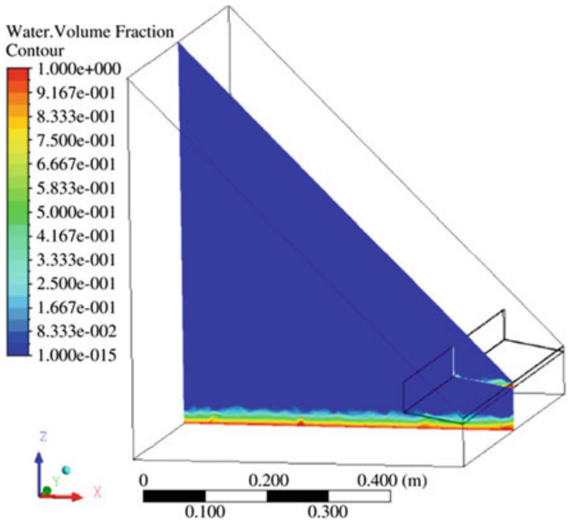
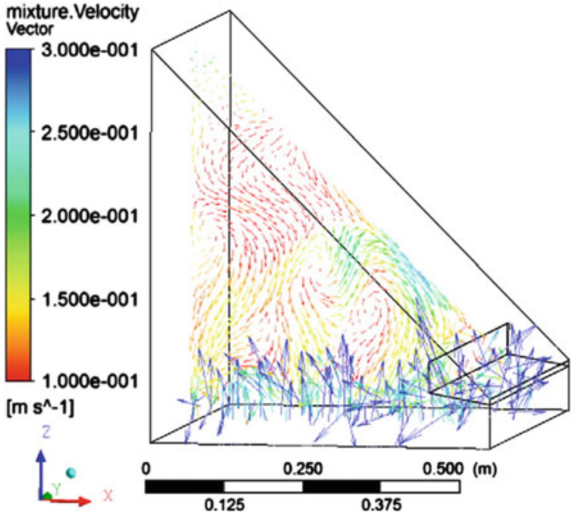


Fig. 14 Volume of water occupied at the *y* axis [8]

were fully converging when the scaled residuals were smaller than certain value which is 10^{-3} other than energy equation which is 10^{-6}. The assumption was made that grid interdependency is in consideration when changes in Nusselt number and productivity are less than 3.2 and 5%. The CFD simulation indicated a positive reading on comparing the experimental readings. Some of the mass, momentum and energy of the governing dimensionless equations for simulations are as follows:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{12}$$

Fig. 15 Velocity of the gas mixture [8]



$$U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = -\frac{\partial P}{\partial x} + Pr\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) \tag{13}$$

$$U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -\frac{\partial P}{\partial y} + Pr\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) + Ra \cdot Pr \cdot (\theta + \mathrm{Br} \cdot C) \tag{14}$$

$$U\frac{\partial \theta}{\partial x} + V\frac{\partial \theta}{\partial y} = \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2}\right) \tag{15}$$

$$U\frac{\partial C}{\partial x} + V\frac{\partial C}{\partial y} = \frac{1}{Le}\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) \tag{16}$$

Here, Pr, Ra and Br are the Prandtl number, Rayleigh number and Buoyancy ratio, where

$$\theta = \frac{T - T_\mathrm{g}}{T_\mathrm{v} - T_\mathrm{g}}, C = \frac{C - C_\mathrm{g}}{C_\mathrm{v} - C_\mathrm{g}}, U = u \cdot \mathrm{Rd}/\gamma, V = v \cdot \mathrm{Rd}/\gamma$$

All Eqs. (12)–(16) had assumption that the temperature was constant between water and glass and the boundary is adiabatic in nature. Also the assumption that the air is an ideal incompressible gas with no changes in physical aspects and viscosity were taken into account. Taking all these factors into account, a conclusion was drawn.

The CFD simulation indicated a re-circulating zone with a clockwise direction in the enclosure. The results also implied that formation of water droplets mostly takes place on the upper area of the glass cover. This detailed description of results shows that explanation of events taking inside a still can be evaluated using CFD simulation. Hence, the simulation provides a deeper understanding of the events. This is due to

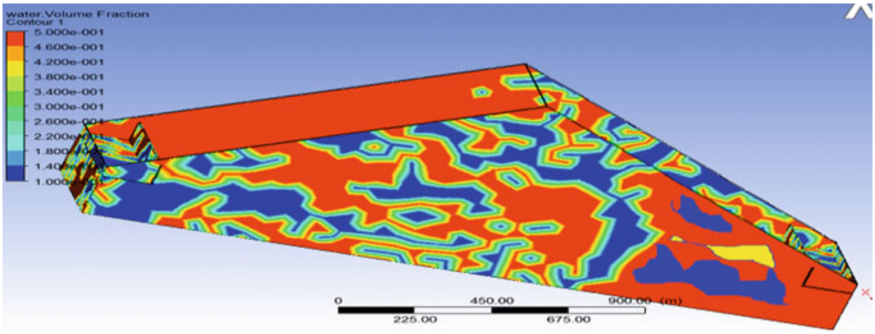


Fig. 16 Fraction of water volume in the solar still

the availability of a large amount of data, followed by an increase in the accuracy of the readings.

A CFD analysis was conducted for a single-basin double-slope solar still. The still modelling was done in SOLIDWORKS software. After that the meshing was done in ANSYS ICEM CFD. Regarding the boundary conditions, an assumption that the evaporation is taken to be laminar is taken into account. Moreover, there is a proper separation between solid and liquid phases; hence, it can be said that the phases are continuous. Now the productivity of a solar still depends on various parameters such as inclination angle and water depth. In order to take all these parameters into account, CFD simulation is used. The simulation was carried out in CFD CFX 14. CFD analysis was done for different months of solar irradiance. The following figures are the CFD simulations of the TBSS.

Figures 16 and 17 show that the water droplets are formed on the glass as the water gets heated. The temperature of the water is higher than that of the glass cover. The sole cause of condensation was the difference in temperature between the water and the glass surface.

From Figs. 18 and 19, the simulation was found to be done between temperatures of 30–60 °C. Here, the bottom part has the maximum temperature as can be seen from the diagram and the upper part has the least temperature. The result obtained was that the amount of water evaporated was equal to the amount of water condensed. This shows that the CFD is a useful tool for the prediction of the rate of productivity.

An ANSYS simulation was carried out using two 3D phase models each for the evaporation and the condensation processes [10]. Initially, a model of the hemispherical still was made using SOLIDWORKS software. After that the model was put to simulation. Now for solving the continuity and momentum equations, boundary conditions were given. The simulation was carried out in 9 steps individually. Since the experimental process took 9 h and was in an unsteady state, it was assumed that for every one hour, the temperature was constant for the water and the glass.

Again another assumption was made that the amount of water evaporated and the amount of distillation of water taken place are equal. To improve the accuracy of the results, the adhesion and cohesive forces due to a single water droplet were taken

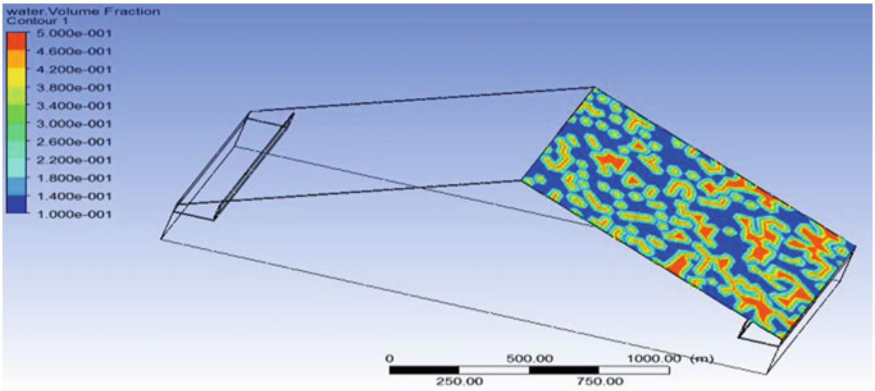


Fig. 17 Fraction of water volume at the right

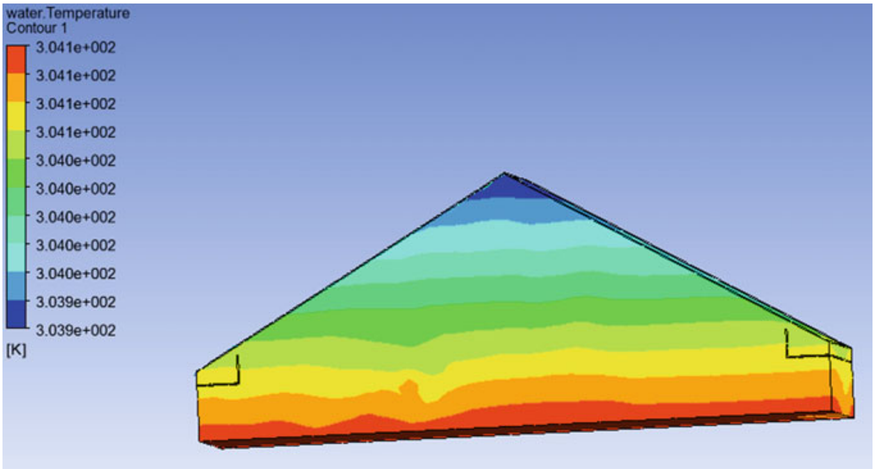


Fig. 18 Distribution of water temperature

into consideration. During the end of the simulation, the amount of water decreases slightly; hence, the same amount of water is poured to keep the balance. Finally, the CFD results were in good agreement with the experimental results. A similar work on experimental and ANSYS CFD simulation analysis was done on hemispherical solar still [11]. The difference between the two papers was as follows: [10] did a modelling and verification hence it included the governing equations of mass, momentum and energy conservation, whereas [11] carried out the analysis of the simulation and the experimental process. Altogether the modelling paper stressed on the design of the still and the temperature and solar radiation during various hours of the experiment, and the analysis included the simulation results and graphical data of the comparison of the experimental and simulation results. Figures 20, 21, 22, 23, 24, 25, 26, 27,

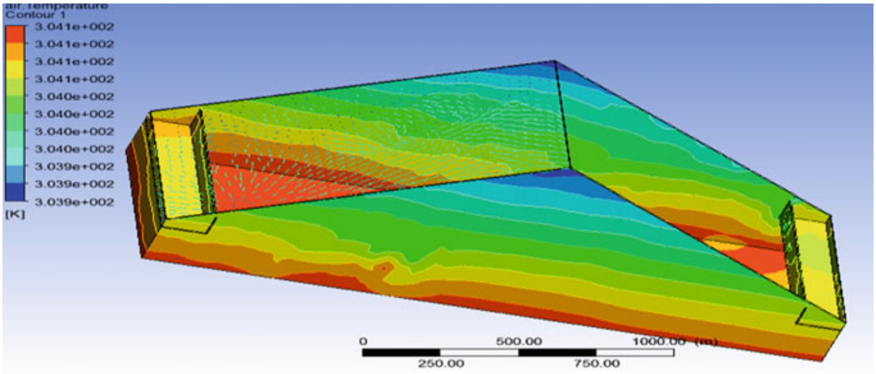


Fig. 19 Distribution of temperature of air inside the still

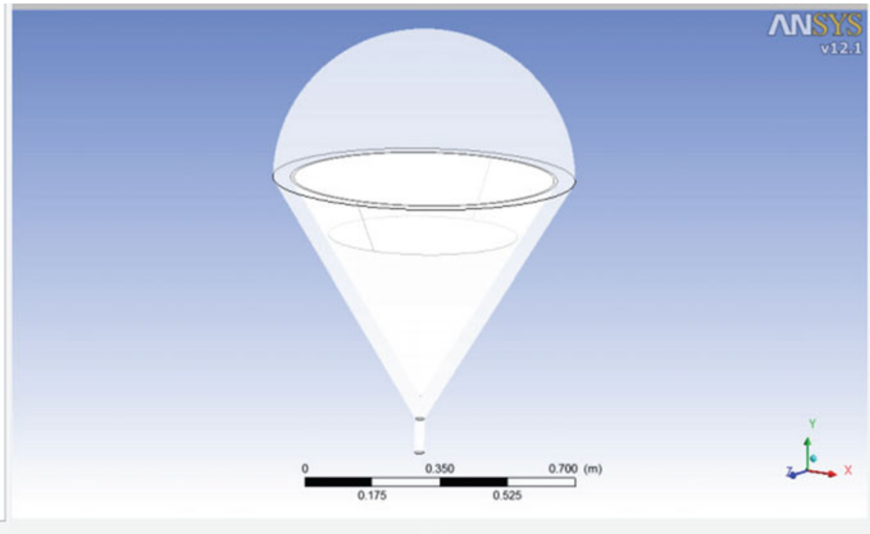


Fig. 20 Steady-state condition of the still [10]

28, 29, 30, 31 and 32 illustrate the CFD simulations of the still. Figure 20 shows the condition of the still at the steady state.

Figures 21 and 22 show the region of vapour and water formed in the still.

Figures 24, 25, 26, 27, 28, 29, 30 and 31 show the simulation results of various conditions of temperature during the period of 9 a.m.–4 p.m. Finally, taking these detailed processes inside the still into account and the simulation results with the experimental results, a statement can be concluded that CFD is a useful software for carrying out any analysis and simulations reducing the cost of experimental process. Considering the fact that it can take into account so many cases that take place in a

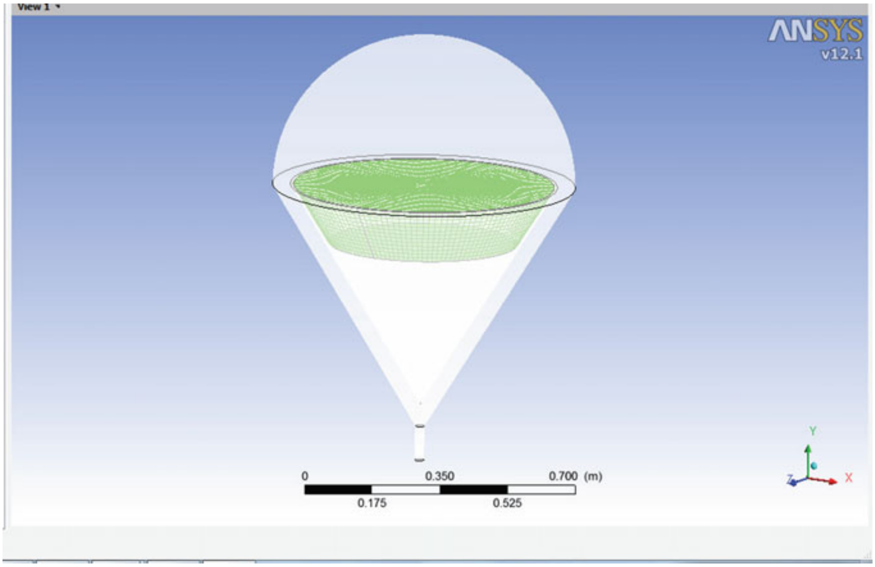


Fig. 21 Region of water [10]

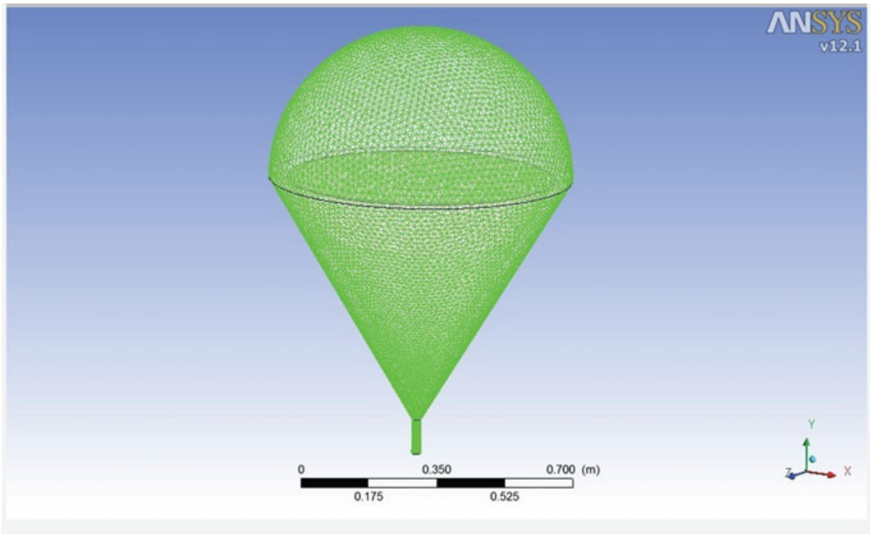


Fig. 22 Area of vapour [10]

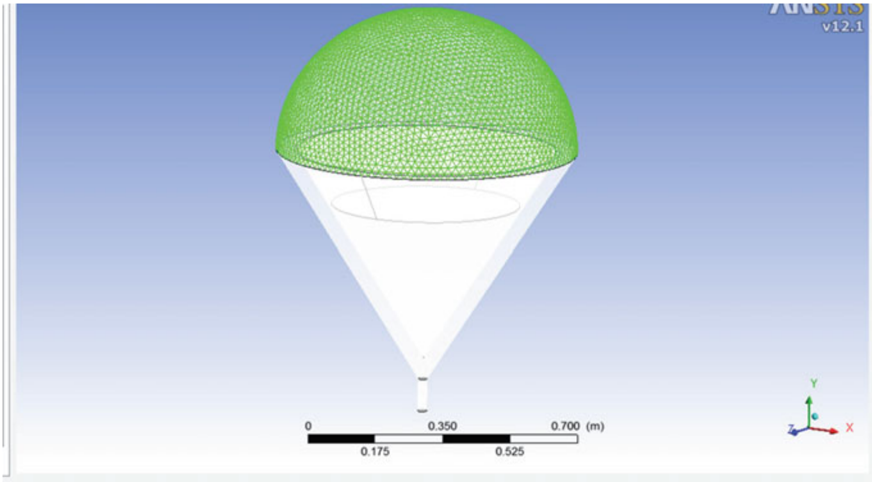


Fig. 23 Area of solar radiation [10]

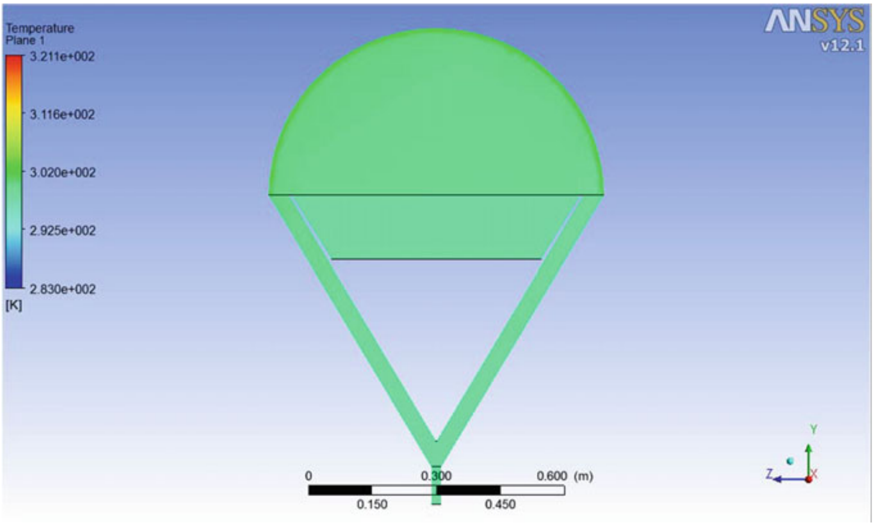


Fig. 24 Temperature diagram at 9 a.m. [11]

still and still provide a good value, a conclusion can be made that CFD behaves very much like modelled real-life experiments.

A liquid-and-gas-phase 3D model was used for the change of state of water for each process taking place in a single-slope solar still (SSS) by utilizing CFX method for the simulation [12]. The heat and mass transfer coefficient is greatly dependent on the performance parameter of the still. Hence, the general transfer equations have been denoted by Eq. (17):

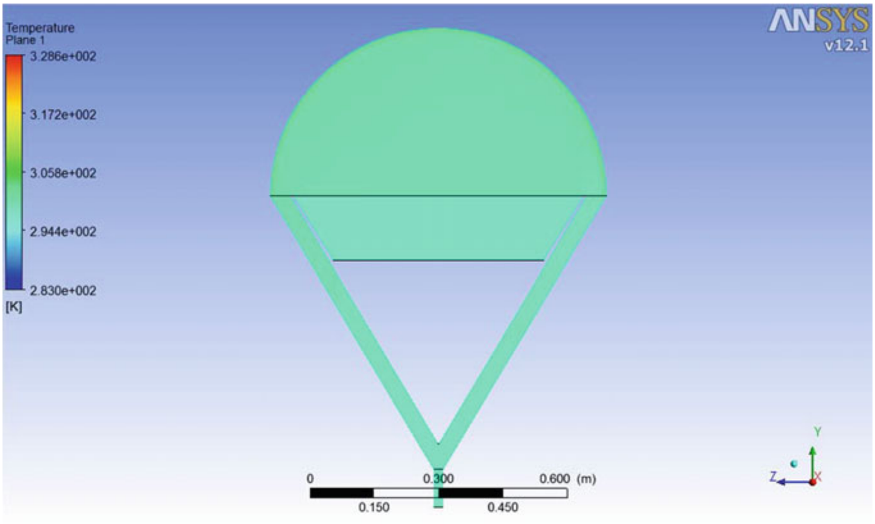


Fig. 25 Temperature diagram at 10 a.m. [11]

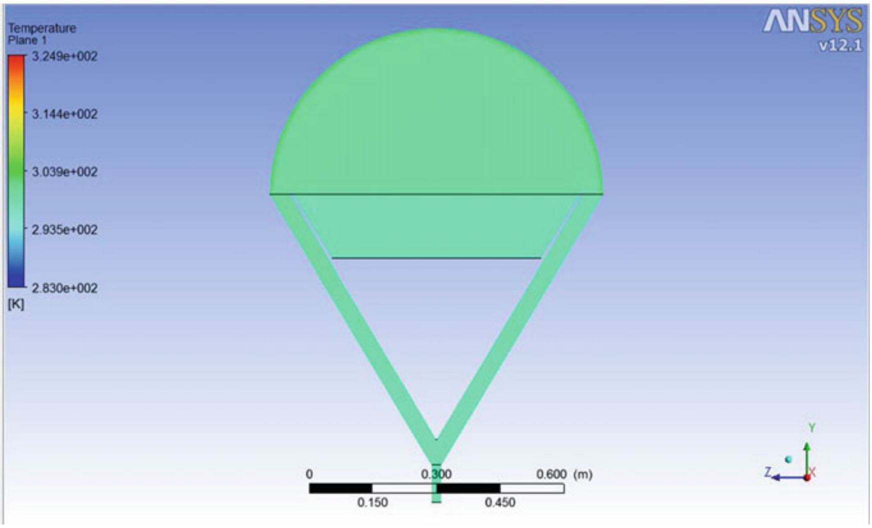


Fig. 26 Temperature diagram at 11 a.m. [11]

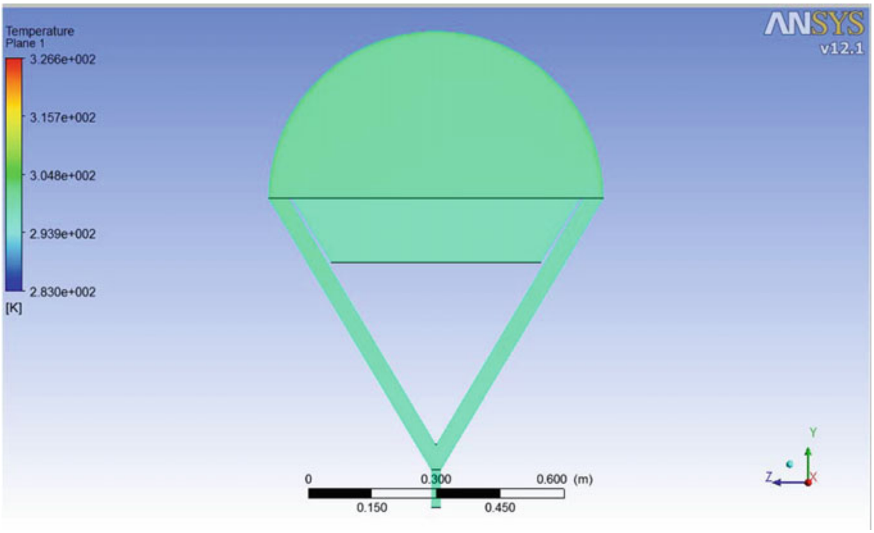


Fig. 27 Temperature at 12 p.m. [11]

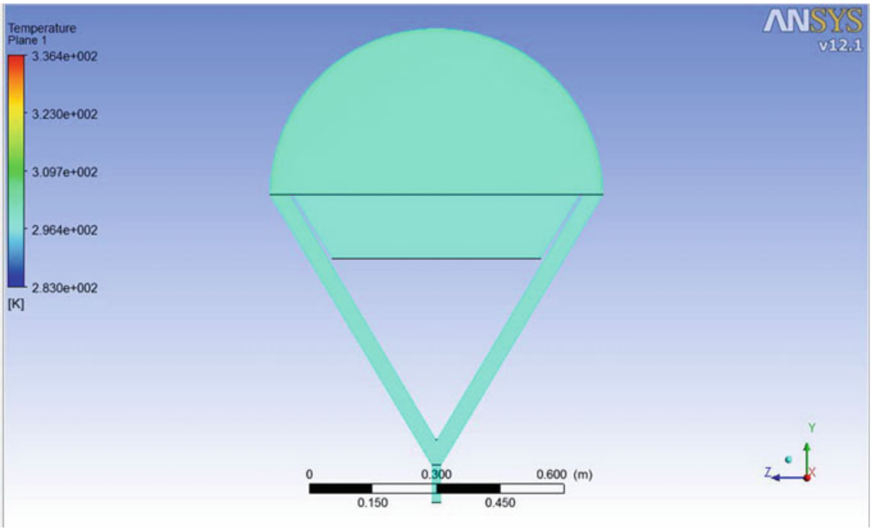


Fig. 28 Temperature diagram at 1 p.m. [11]

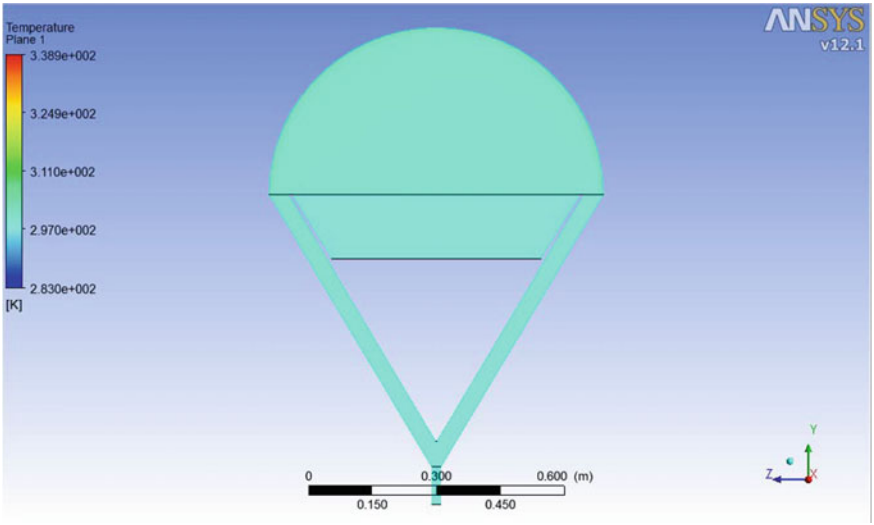


Fig. 29 Temperature diagram at 2 p.m. [11]

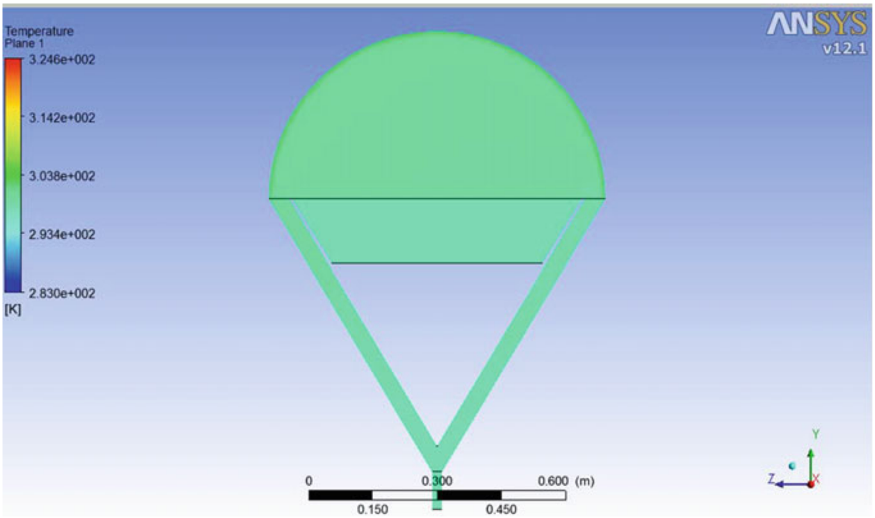


Fig. 30 Temperature diagram at 3 p.m. [11]

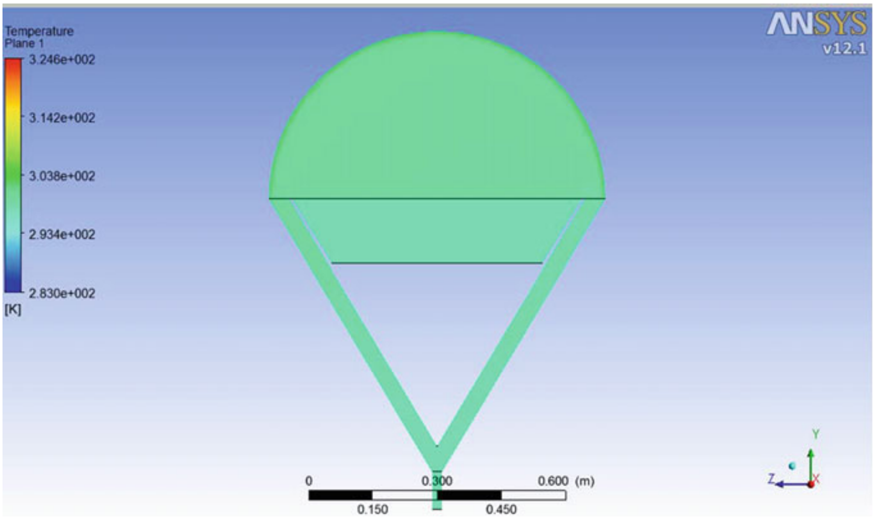


Fig. 31 Temperature diagram at 4 p.m. [11]

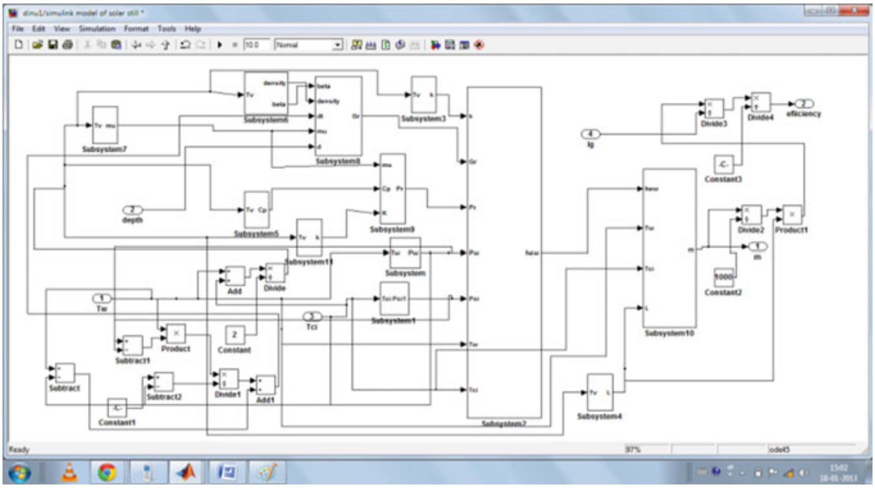


Fig. 32 MATLAB model of the still [23]

$$q = h(T_v - T_g) \tag{17}$$

where h varies and hence q varies according to radiative, convective and evaporative heat transfer coefficients. The rate of water formation and the heat transfer coefficient of each of the cases (convective, evaporative, radiative) and also the temperature of the glass and water had a good relation between the experimental values. Hence, it can be concluded that CFD is a powerful tool for carrying out simulations.

A review on the latest developments using solar still was provided in [13]. The review revealed that CFD is a better tool for simulations in the future of solar still study. Various parameters can be taken into consideration for the solar still study in CFD simulation such as the reflectors, storage materials, etc. Also, CFD is a useful tool for use in the field of nanotechnology.

2.2 MATLAB Simulation

A study of a modified basin type solar still (BSS) which has a condenser was simulated using MATLAB [14].

The modified still productivity was compared with that of the traditional basin type still. The climatic conditions were based on the local climatic conditions, i.e. Cairo, Egypt. The following are few of the energy balanced equations used in the mathematical modelling for glass cover, salt water and still base:

$$\alpha_{\text{glass}} A_{\text{glass}} I_T + \dot{m}_{\text{wg}}\left(h_{\text{fg}} + C_{\text{wg}}\left(T_{\text{v}} - T_{\text{g}}\right)\right) + \varepsilon_{\text{eff}} \sigma A_{\text{B}}\left((T_{\text{w}} + 273)^4 - \left(T_{\text{g}} + 273\right)^4\right) = \dot{Q}_{\text{glass}} + m_{\text{glass}} c_{\text{glass}} \Delta T_{\text{glass}} / \Delta t \quad (18)$$

$$h_{\text{v}} A_{\text{b}}(T_{\text{b}} - T_{\text{v}}) + \frac{k_{\text{w}} A_{\text{b}}(T_{\text{b}} - T_{\text{v}})}{d_{\text{w}}} + \varepsilon_{\text{eff}} \sigma A_{\text{b}}\left((T_{\text{b}} + 273)^4 - (T_{\text{v}} + 273)^4\right) = m_{\text{water}} c_{\text{water}} \Delta T_{\text{water}} / \Delta t + \dot{m}_{\text{wt}} h_{\text{fg}} + \varepsilon_{\text{eff}} \sigma A_{\text{b}}\left((T_{\text{v}} + 273)^4 - \left(T_{\text{g}} + 273\right)^4\right) \quad (19)$$

$$\alpha_{\text{base}} \varphi_{\text{g}} \varphi_{\text{w}} A_{\text{b}} I_{\text{t}} = \dot{Q}_{\text{b}} + h_{\text{v}} A_{\text{b}}(T_{\text{b}} - T_{\text{v}}) + \frac{k_{\text{w}} A_{\text{b}}(T_{\text{b}} - T_{\text{v}})}{d_{\text{w}}} + \varepsilon_{\text{eff}} \omega A_{\text{b}}\left((T_{\text{b}} + 273)^4 - (T_{\text{v}} + 273)^4\right) \quad (20)$$

These mathematical models were all solved using the MATLAB software. The simulation results were carried out in the climatic condition of the area. The simulation results were more or less similar to the experimental results. The simulation results had deviated for small areas because of taking into account uncertain values during the calculation of the heat transfer coefficient and the solar radiation. For the simulation, several parameters were taken into consideration like the velocity of the wind and angle of inclination. for the production rate and the efficiency. The simulation gave relations between the various parameters which affect the productivity of the still. The relations are the height of water and the velocity of wind is inversely related to the productivity. The inclination angle during the summer months had an inverse impact on the productivity, whereas during the winter, it had direct impact on the productivity. Also lowering the glass cover thickness of the still increases the heat transfer rate and hence increases the productivity, and with absorptivity, the output of the still increases. Altogether MATLAB was useful for finding out the efficiency, amount of water produced throughout the year, for making more effective designs and for analysing the situations taking place in the still.

The effect of thermal energy storage system in a weir type cascade solar still was studied [15]. The study was carried out in MATLAB software once using phase change material (PCM) and once without PCM. The PCM for this case was paraffin wax. The film coefficient and few of the parameters were studied such as the water depth and the effect of distillate due to the distance of the water and the glass cover rate. Finally, the resulting data revealed PCM had an increase in productivity compared to no PCM.

The effect of depth of water on the various mass transfer coefficients was studied for a single-slope solar still [16]. MATLAB software was used for calculating different heat transfer coefficients such as the evaporative, radiative and convective. A solar still having an evacuated tube collector with forced convective mode of heat transfer was experimented and simulated [17]. A thermal model was developed to predict the productivity of the still. Heat balance and energy equations were used to predict the model. Few of these equations are as follows:

$$\dot{\alpha}_{\text{glass}} \cdot I_{\text{s}}(t) \cdot A_{\text{glass}} + h_{\text{v}} \cdot A_{\text{a}} \cdot \left(T_{\text{sw}} - T_{\text{gin}}\right) = h_{\text{glc}} \cdot A_{\text{glass}} \cdot \left(T_{\text{gin}} - T_{\text{gout}}\right) \tag{21}$$

$$h_{\text{glc}} \cdot A_{\text{glass}} \cdot \left(T_{\text{gin}} - T_{\text{gout}}\right) = h_{p} \cdot A_{\text{glass}} \cdot \left(T_{\text{gout}} - T_{\text{am}}\right) \tag{22}$$

The mathematical model was solved using MATLAB. The motive of MATLAB usage here was to solve the temperature efficiency and the emissivity of the still. The final output was that the evacuated tube collector used in the still increases the production of water in the still.

A solar still was designed and tested, which was having vapour adsorption basin [18]. Experimental and theoretical models were made and compared for the regular solar still. For the theoretical study, the mathematical model was made and was solved using MATLAB. Following represent few of the modes of heat transfer equations used in the simulations.

$$\dot{Q}_{\text{convective,Bs}-\text{v}} = h_{\text{convective,Bs}-\text{v}} A_{\text{Bs}} (T_{\text{Bs}} - T_{\text{v}}) \tag{23}$$

$$\dot{Q}_{l} = U_{\text{basin}} A_{\text{Bs}} (T_{\text{Bs}} - T_{\text{am}}) \tag{24}$$

$$\dot{Q}_{\text{convective,v}-\text{g}} = h_{\text{convective,v}-\text{g}} A_{\text{v}} \left(T_{\text{v}} - T_{\text{g}}\right) \tag{25}$$

$$\dot{Q}_{\text{radiative,v}-\text{g}} = h_{\text{radiative,v}-\text{g}} A_{\text{v}} \left(T_{\text{v}} - T_{\text{g}}\right) \tag{26}$$

$$\dot{Q}_{\text{evaporative,v}-\text{g}} = h_{\text{evaporative,v}-\text{g}} A_{\text{v}} \left(T_{\text{v}} - T_{\text{g}}\right) \tag{27}$$

$$\dot{Q}_{\text{radiative,g}-\text{sky}} = h_{\text{radiative,g}-\text{sky}} A_{\text{g}} \left(T_{\text{g}} - T_{\text{sky}}\right) \tag{28}$$

$$\dot{Q}_{\text{convective,g-sky}} = h_{\text{convective,g-sky}} A_{\text{g}} \left(T_{\text{g}} - T_{\text{sky}} \right) \tag{29}$$

Each of the above heat transfer Eqs. (23)–(29) used in the MATLAB had different heat transfer coefficients having different values since evaporative, convective and radiative. These equations were used to determine the absorption rate. The theoretical data were in good agreement with the experimental data. The difference between the experimental and theoretical data had a maximum value of 2.3%. This finally brings to an important conclusion that MATLAB is a useful tool to carry out simulations as it has very low percentage of error associated in its final results.

A theoretical study of passive solar still having evaporator and condenser in separate chambers was conducted [19]. MATLAB program was used to solve the mathematical model made. The energy and heat transfer equation of the glass is given as follows:

$$\begin{aligned} m_{\text{glassc}} C_{p,\text{glassc}} \frac{\mathrm{d}T_{\text{glassc}}}{\mathrm{d}t} = {} & A_{\text{glassc}} F_{\text{glassc}} G_{\text{eff}} + A_{\text{v}_1} h_{\text{glassc}} \left(T_{\text{v}_1} - T_{\text{glassc}} \right) \\ & - A_{\text{glassc}} h_{\text{c,glassc-am}} \left(T_{\text{glassc}} - T_{\text{am}} \right) \\ & - A_{glassc} h_{\text{rad,glassc-sky}} \left(T_{\text{glassc}} - T_{\text{sky}} \right) \end{aligned} \tag{30}$$

$$h_{\text{glassc}} = \left(\frac{R h_{\text{c,v}_1\text{-glassc}}}{1 + R} + \frac{R h_{\text{e,v}_1\text{-glassc}}}{1 + R} + h_{\text{rad,v}_1\text{-glassc}} \right) \tag{31}$$

The simulation revealed that various parts of the still had an increased temperature compared to the state at room temperature of the material during the day time and the temperature was less during the night, which is a general case due to direct sunlight. Also the values obtained at different ranges of temperature were in good agreement with the earlier studies.

The performance of a solar still integrated with evacuated tube collector was obtained [20]. The productivity of the still was predicted for various parameters such as energy and energy efficiency. A mathematical model of energy conservation was made for each of the parameters with few assumptions and was solved using MATLAB. Like one of the previous simulations, here also MATLAB is used for finding out the temperatures of the various parts of the still and also the efficiency and the emissivity of the still. Hence, it can be said that MATLAB simulations can be very much useful for finding out few parameters like temperature and efficiency.

A theoretical study of simple solar still coupled to a compression heat pump [21]. A mathematical model was made using the energy and mass conservation equations. The model was solved using MATLAB simulation, and it predicted that the efficiency of the modified still was 75% higher than the original simulation. These are few of the energy equations used in the model by the evaporator, water, absorber, and glass cover.

Glass cover:

$$\dot{m}_{\text{glass}} \cdot c_{\text{glass}} \cdot \frac{\mathrm{d}T_{\text{g}}}{\mathrm{d}t} = \left(1 - \beta_{\text{glass}}\right) \cdot \alpha_{\text{glass}} \cdot g_h + \left(q_{\text{evaporation,v-glass}} + q_{\text{radiation,v-glass}} + q_{\text{convective,v-glass}}\right) - q_{\text{radiation,glass-am}} - q_{\text{convective,glass-am}} \quad (32)$$

Evaporator:

$$\dot{m}_{\text{ev}} \cdot c_{\text{ev}} \cdot \frac{\mathrm{d}T_{\text{ev}}}{\mathrm{d}t} = q_{\text{convective,v-ev}} + q_{\text{evaporation,v-ev}} - q_{\text{evaporation,f}} \quad (33)$$

Water:

$$\dot{m}_{\text{water}} \cdot c_{\text{water}} \cdot \frac{\mathrm{d}T_{\text{water}}}{\mathrm{d}t} = \left(1 - \beta_{\text{glass}}\right) \cdot \left(1 - \alpha_{\text{glass}}\right) \cdot \alpha_{\text{water}} \cdot g_h - \left(q_{\text{evaporation,v-glass}} + q_{\text{radiation,v-glass}} + q_{\text{convective,v-glass}}\right) \cdot \frac{A_{\text{glass}}}{A_{\text{water}}} + q_{\text{convection,b-v}} + \frac{w}{A_{\text{water}}} \quad (34)$$

Absorber:

$$\dot{m}_{\text{Bs}} \cdot c_{\text{Bs}} \cdot \frac{\mathrm{d}T_{\text{Bs}}}{\mathrm{d}t} = \left(1 - \beta_{\text{glass}}\right) \cdot \left(1 - \alpha_{\text{glass}}\right) \cdot \left(1 - \alpha_{\text{water}}\right) \cdot \alpha_{\text{Bs}} g_h - q_{\text{convection,Bs-v}} - q_{\text{loss}} \quad (35)$$

Equations (32)–(35) of energy balance equations were solved simultaneously by the fourth-order Runge–Kutta method in MATLAB.

Few other assumptions were made during the simulation, which included the initial temperature was equal to the ambient temperature, and on these values, the properties and the heat transfer coefficients were assumed. The obtained reading of the theoretical analysis was compared with the experimental data, and it was in good agreement with the experimental data. Altogether, the basic parameters and the operating boundaries of the still were constant during the simulation. Hence, MATLAB simulation is a good tool for finding out the efficiency of modified stills and also helps in understanding the parameters affecting the productivity of the modified stills.

A program was developed to find the effect due to a symmetric double-slope solar still and its productivity in comparison with the asymmetric double-effect solar still [22]. The MATLAB 7 program was used for solving the equations and the simulation results. Finally, a result was obtained that the simulation results showed the optimum angle for radiation is 10°.

An analysis of amount of productivity of a single-slope solar still (SSSS) was done. A mathematical model was made for the SSSS [23]. The simulation was carried out in the MATLAB Simulink model. The following are the relations between the convective and evaporative heat transfer equations which were solved using the MATLAB:

$$h_{\text{e,v}} = 0.016273 \cdot h_{\text{c}} \cdot (P_{\text{v}} - P_{\text{ci}})/T_{\text{v}} - T_{\text{gin}}) \tag{36}$$

$$h_{\text{e,w}} = 0.016723 \cdot \left[(K/A)C(Gn \cdot Pr)^{n} \cdot \left(P_{\text{v}} - P_{\text{ci}}/T_{\text{v}} - T_{\text{gin}}\right)\right] \tag{37}$$

$$q_{\text{e,v}} = 0.016273 \cdot \left[(K/D)C(Gn \cdot Pr)^{n} \cdot \left(P_{\text{v}} - P_{\text{ci}}/T_{\text{v}} - T_{\text{gin}}\right) \cdot \left(T_{\text{v}} - T_{\text{gin}}\right)\right] \tag{38}$$

Figure 32 shows the MATLAB simulink block diagram used for the simulation. The various parameters of the still were individually assessed. The simulation gave an inverse relation between the internal film coefficient and the height of the water due to temperature change. The experimental reading was in good agreement with the simulation reading. A dynamic system simulation study was carried out for showing the usefulness of the SSSS. Also a result was obtained that the inclination of angle 30° was more useful when compared to 23° in every way. Finally, it can be said that MATLAB has a very good use in simulation. It differs from CFD in pictorial analysis which means that it cannot produce pictorial diagram of the body and give individual analysis of the entire still, but nevertheless the final data obtained are very much effective in nature.

2.3 SPSS Simulation

The variables which affected the productivity of a solar still were determined under certain weather conditions [24]. A year-round data for the productivity were collected, and using SSPS software, the general equation was formed for the daily water produced by the still. A basic formula was developed to predict the productivity of the still. The parameters and the boundary conditions of the still were given based on which the formula is given below:

$$P_{\text{d}} = -1.39 + 0.894H + 0.033t_{\text{a}} - 0.017W - 0.008\phi - 1.2(\lambda/\varphi) \tag{39}$$

Equation (39) was obtained using multiple linear regression technique. The value of multiple correlation coefficients (R) was calculated. Finally, comparing the simulation data with the experimental data, a good correlation was established. Hence, it can be seen that SPSS is a useful software for finding out the productivity.

A performance evaluation was done on a solar still. ANOVA test was done here with SPSS 16 software to find out the significance in the pre-treatment between different substrates.

A study of usage of various adsorbent and insulators for a basin still was conducted [25]. SPSS was used for analysing the changes in the means of productivity of the obtained fresh water to various temperatures at each stage of affecting materials and vice versa. Using ANOVA, the significant value was found to be less than 0.05 and the interaction was 0.009. The *R* value was shown to be 0.521, which is 52% production of fresh water from the distiller. All these results show that the model was a good model. A relation between the temperatures of the basin, the water and the external basin showed that the temperatures had interactions which mean that there is equilibrium between the temperatures. This leads to a conclusion that SPSS can be used for overall comparison of the experiment and model the value graphically.

A study of the ability of success in making a model of thermal efficiency of a solar still using the data of its operations and its surrounding weather conditions was carried out. There was both MLP and MNR models for calculating the productivity. The MLR model was made using the IBM SPSS statistics 22. The MLR model was carried out with the same experimental values as the MLP. As a result, a mathematical relation was established with the nine independent variables like velocity of wind, air temperature and humidity. Hence, SPSS can be used for making MLR model, and the results obtained are in good relations with the experimental data.

A study on the effect of ANN model for describing the outcome of the solar still was carried out, but agricultural drainage water was used as a source of water for the still [26]. The MLR model was made using SPSS software. Finally, it can be concluded that SPSS is a useful tool for carrying out simulations and model making.

2.4 FORTRAN Simulation

A theoretical investigation of the amount of radiation taking place on the impure water after striking the glass material cover of the stepped solar still was conducted [27]. FORTRAN programming was used to study the effect of shape due to radiation for different inclination angles. From the FORTRAN programming results, a relation was obtained which showed that the production of fresh water was more when radiation shape factor was taken into consideration. The formula for finding the amount of productivity other than the heat transfer and energy balance equations is shown below:

$$m_{\text{productivity}=\frac{Q_{\text{evaporation}}}{L_{\text{v}}}} \tag{40}$$

Calculation of the percentage of productivity by calculating the radiation due to change in shape parameter to distillate the productivity and without calculating the radiation due to change in shape parameter is as follows:

$$\varsigma = \frac{(m_{\text{evap}})_{\text{with}} - (m_{\text{evap}})_{\text{without}}}{(m_{\text{evap}})_{\text{without}}} \times 100 \tag{41}$$

Finally, it can be concluded that FORTRAN programming is a useful to for finding out the effect due to individual parameters.

An experimental and mathematical study of the addition of solar reflector and collector in a simple solar still (SSS) was conducted [28]. The mathematical model in the form of differential equations was solved by the fourth-order Runge–Kutta method. The entire process is done in FORTRAN language. The program was also used to predict the changes in temperature per hour for the various parts of the solar still and also to predict the amount of clean water obtained and the film coefficient of the still. The equation for the hourly yield is given below:

$$m_{\mathrm{eva}} = U_{\mathrm{eva}} \cdot \left(T_{\mathrm{v}} - T_{\mathrm{gin}}\right) \cdot 3600/L_{\mathrm{v}} \tag{42}$$

Here Eq. (42) m_{eva} is the distillate rate and L_{v} is the latent heat of vaporization and U_{eva} is the film coefficient due to evaporation. FORTRAN language can be used for solving mathematical models predicting various outputs of the still. Hence, the model obtained by the mathematical analysis had a good correlation with the experimental data obtained for the same experiment.

A comparative study on the effects of coupling flat plate and spherical plate solar still collector was done. The thermal modelling differential equations were solved using the fourth-order Runge–Kutta method. Programming was done in FORTRAN language. This takes back to the previous conclusion that FORTRAN is a useful tool for finding out the parameters.

A simulation study of the double-film solar still together with conventional solar still was carried out [29]. The FORTRAN 90 was used for finding out the simulated values. The newly modified still was compared with the original solar still for assessment.

A study on the methods to increase the productivity of fresh water in a solar still by changing glass screen design and amount of solar radiation absorbed between the single slopes and double slopes, hemispherical still was conducted [30]. A fourth-order Runge–Kutta was used for solving equations. The programs for finding out the various parameters were made using FORTRAN language. Hence, based on the previous analysis, a conclusion can be made that FORTRAN is one of the useful tools which is favoured for finding individualistic parameters.

A study of the ability of single and double stills to be used in the daily purpose for economic use and also the energy transfer processes of the stills and its surroundings was carried out [31]. Heat and mass transfer equations were used for the modelling. The equations were fourth-order differential equations solved by using the method of Runge–Kutta in FORTRAN language. The final results obtained were used for analysis of the feasibility of the stills.

2.5 MATLAB Simulation on Single-Stage Active Still

Studying of a single-slope solar still contains a fluid for supplying heat energy to the liquid [32]. The energy equations were solved using the MATLAB model. The MATLAB equation was based on the command ode 15s, which is faster than the command ode 45. The energy equations were generally the parameters of the stills such as inner glass cover and outer glass cover. The mass balance equations are illustrated below:

$$m'_{\mathrm{SW}} = m'_{\mathrm{ev}} + m'_{\mathrm{b}} \tag{43}$$

$$m'_{\mathrm{SW}} y_{\mathrm{SW}} = m'_{\mathrm{b}} y_{\mathrm{b}} \tag{44}$$

$$m'_{\mathrm{b}} = \frac{1}{\chi} m'_{\mathrm{sw}} \tag{45}$$

$$m'_{\mathrm{ev}} = \frac{1-\chi}{\chi} m'_{\mathrm{sw}} \tag{46}$$

The simulation results gave a significant relation between the speed of the wind and its effect in the production of amount of distilled water. Also it showed that water depth had a significant relation with the production of fresh water.

ANN model was used to study the productivity of a triple-slope solar still [33]. Three ANN models were made and solved using MATLAB models such as the feed-back network model, the Elman model and the NARX model. For the NARX model, there was 3 types of neuron numbers, each created and solved using MATLAB. The data consisted of 46 samples, which were taken as input data for the ANN model. Finally, the results were that the feed-forward model had the best results compared to the other two models.

An optimization of the number of collectors was done for PV/T hybrid solar still [34]. The software used was MATLAB 7 for solving the equations, few of which were involved of heat and mass transfer and energy equations. Finally, the hourly variations were found out.

A study of a modified still, which has three different designs of cover each having different amount of productivity, was done [35]. A MATLAB program was used for development of the model. Also the MATLAB program was used to find the various relations between the different parameters of the still. The result obtained was that no model had a good output over the range of considered months on comparison. The result obtained by the MATLAB simulation was not in good agreement with the experimental data due to the variation in parameters.

A study to find the inner and outer glass covers of an active solar still was conducted [36]. MATLAB program was used here in order to calculate the various film coefficients. Further, these values will be used for calculating the theoretical values of various parameters. From the above procedure, it can be said that MATLAB is useful for making and validating experimental models.

2.6 FORTRAN Simulation of Active Solar Still

A study of a modified double-slope active solar still and a numerical investigation for the still were carried out [37]. The numerical model was solved using FORTRAN 6.6 computer program. The program solved energy equations of still such as the basin, water and cover of the still. All the main energy equations were solved using the fourth-order Runge–Kutta method. The final results of the simulation displayed the relation of the temperature effects and fresh water productivity.

2.7 CFD Simulation of Multistage Still

A CFD study on novel multistage evacuated solar still using FLUENT software was conducted. The still consisted of three stages, but only one stage was taken for CFD simulation. The model of the still had a finite element analysis (FEA) and a structural analysis using MSC/NASTRAN FEA software. The simulation was done in a 2D model. The FLUENT segregated solver was used for solving the models of transient conditions.

The figures below illustrate the results obtained on CFD simulation.

Figure 33 illustrates the stress conditions of the cylindrical model made after stiffener was added to the walls of the model. Figure 34 shows the liquid mixture of water as a fraction of volume. It can be seen that the maximum liquid water is formed at the base of the still. The simulation result was very handful for the development and for implementing new designs. Hence, it can be concluded that CFD can be used not only for comparison between experimental and theoretical analyses but also for finding out the relation between various parameters.

A new multistage solar still was designed for increasing the amount of fresh water produced and also to increase the efficiency over the conventional simple solar still [38]. CFD FLUENT software was used to find out the heat and mass transfer rates of the still. The structure was made using NASTRAN software. The stage of the still was modelled using the Gambit pre-processor. The mesh generated was 2D in nature.

Figure 35 represents the overall density of the mixture of water in liquid phase in the simulation. The amount of condensation of water taken place inside the still is shown in Fig. 36. As illustrated from the figure, the condensation is maximum where the evaporation occurs. Figure 37 illustrates the path motion of the vapours where the heavier vapours are moving down and the hot vapours are moving up. The big vortices are away from the smaller ones; also, it can be seen that they are all continuous in nature. Figure 38 illustrates the velocity vectors of the path taken

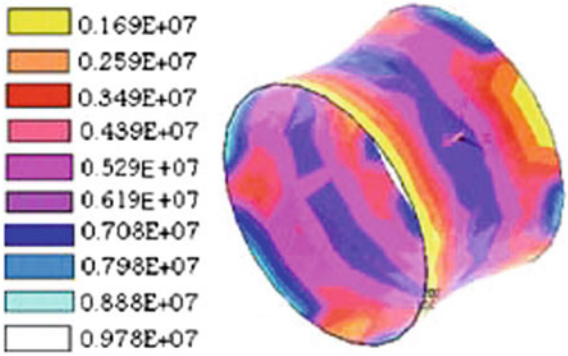


Fig. 33 Stress diagram of the modelled still

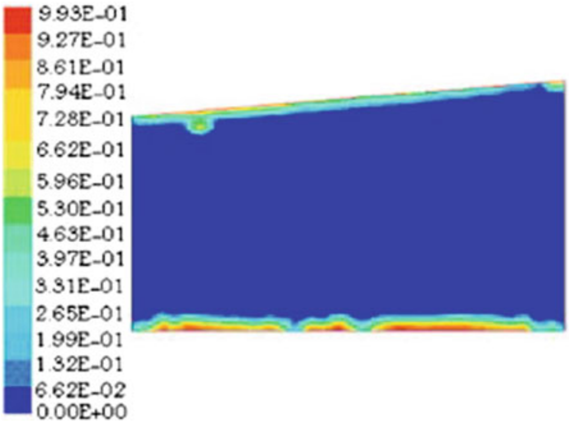


Fig. 34 Diagram of the volume fraction of liquid

by the vortices. The flow pattern is observed from Fig. 39 and can be said that the flow pattern is entirely based on heat transfer process and not by vortex motion. All the simulations were done in order to find out the mechanism behind the heat and the mass flow patterns. The point of interest in the simulations was taken to be the vapour stream lines. Finally, a good result was obtained when compared with the experimental data.

A study to determine the practical design parameters was conducted for a multistage solar still [39]. FLUENT 6.2 software was used for the study. The simulations were done on the basis of energy and mass conservation differential equations taken for each of the stages. Finally, the results obtained had a good relation with the experimentally obtained data.

A numerical investigation and economic benefits were found out for a multistage still under the climatic conditions of the local area which was Batna City [40]. A mathematical model of energy and mass equations was made after which the equations and 3D CFD simulation were done on ANSYS-FLUENT. The simulation shows that there was less amount of energy available, but the amount of water produced had good feedback with the situated conditions.

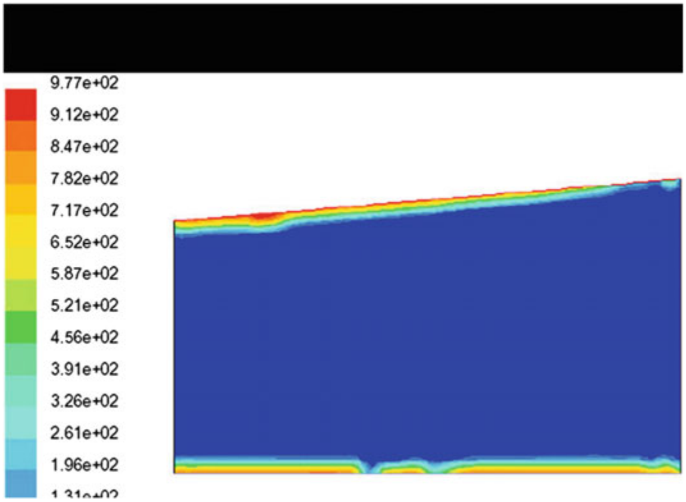


Fig. 35 Liquid water density mixture contour [38]

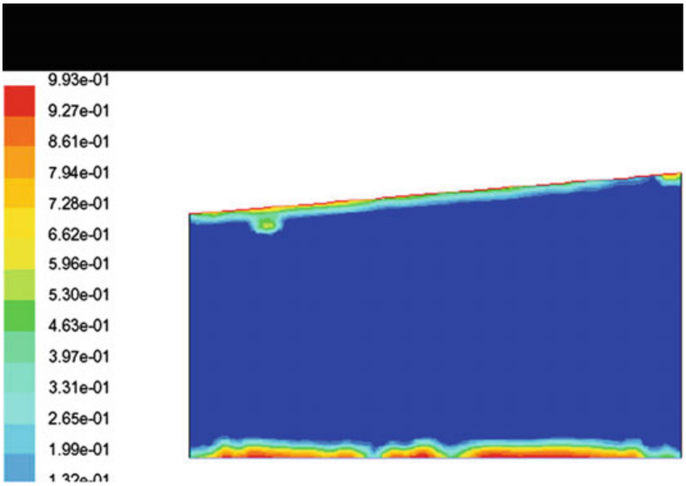


Fig. 36 Volume fraction of liquid water contour [38]

2.8 MATLAB Simulation of Multistage Solar Still

A study on the performance of a solar desalination unit was carried out [41]. The study was carried out using MATLAB 7.0.1. The various important parameters of the still were studied.

A similar optimization and effect of parameter design were studied of a multistage solar desalination system [42]. Like the previous simulation, here also MATLAB

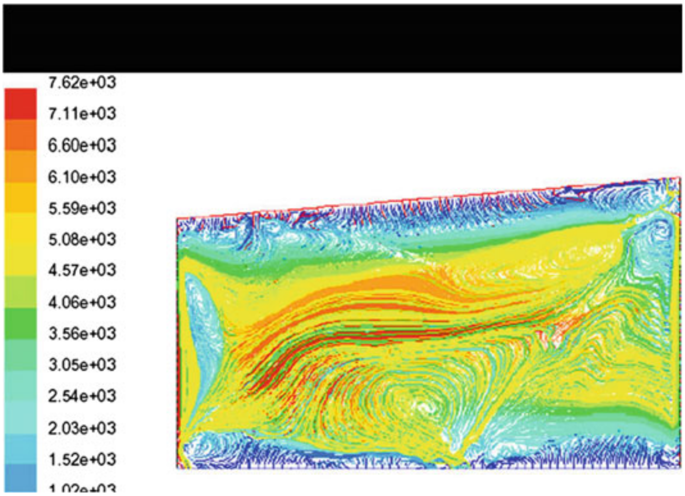


Fig. 37 Mixture path lines for a particular stage in the still [38]

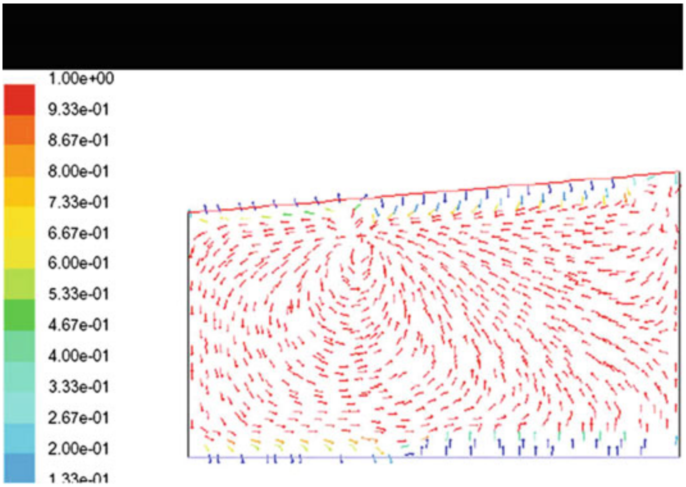


Fig. 38 Velocity vectors of the volume fraction [38]

7.0.1 was used for finding out the various parameters. A good relation was obtained with the MATLAB model when compared with the experimental model.

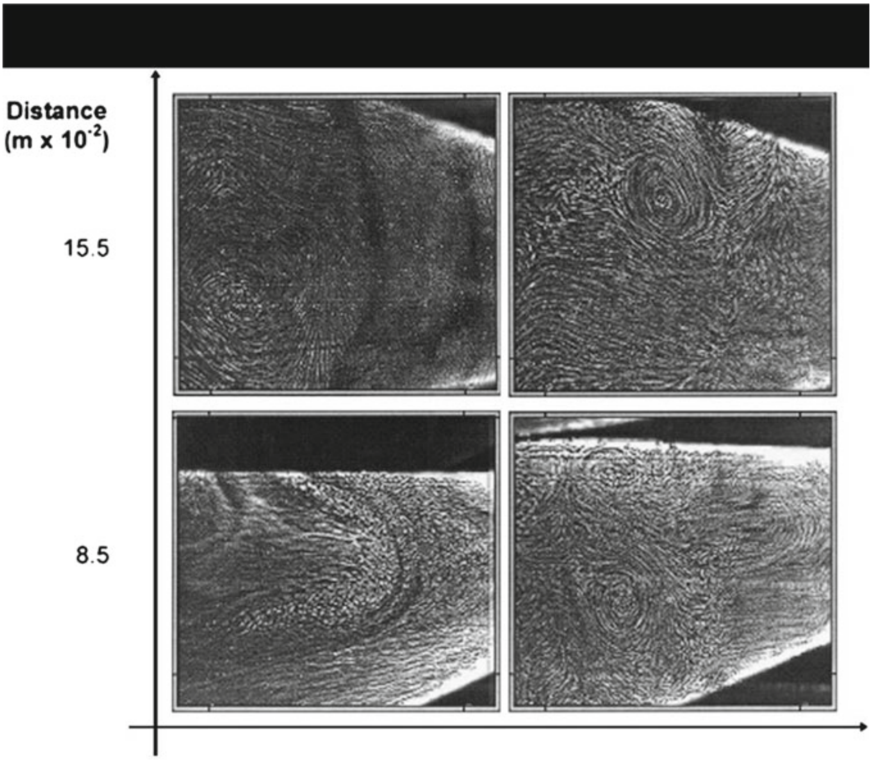


Fig. 39 Flow pattern of water vapour inside a shallow solar still [38]

2.9 FORTRAN Simulation of Multistage Solar Still

A multistage still study and a numerical simulation and also its economic benefits were studied [40]. As mentioned earlier, the multistage still used CFD simulation for studying the energy and mass transfer equations. In addition, the FORTRAN software was used for the analysis of thermal radiation effects on temperature and the amount of water produced on distillation. This shows that a single software may not cover all the studies. Multiple software may be needed for various different parameter analyses; also each software has benefits on the basis of the type of work done: for statistical modelling, SPSS is used quite often; for studying various effects related to the design changes, CFD is used. Altogether it depends on the preference and type of work done by the user.

3 Case Study on CFD Simulation

CFD model was made for the evaporation and the condensation processes of a single-slope solar still. The amount of fresh water obtained during the simulation is the fresh water which is produced inside the solar still. The design and construction were done using ANSYS workbench 10.

3.1 The Boundary Conditions and the Initial Conditions

During the ANSYS, the boundary, continuity and momentum equations are provided. The simulation took place for 8 h from 9 a.m. to 5 p.m. In general, this is a case of unsteady state; hence, to convert it into steady state, the 8 h is divided into 1 h each of steady-state simulation. During every hour, a new constant is taken for the amount of water collected and the glass temperature. The solar radiation mainly depends on the material of the glass, i.e. the amount of radiation it can absorb and amount of radiation the glass emits. For the liquid phase, the wall boundary was

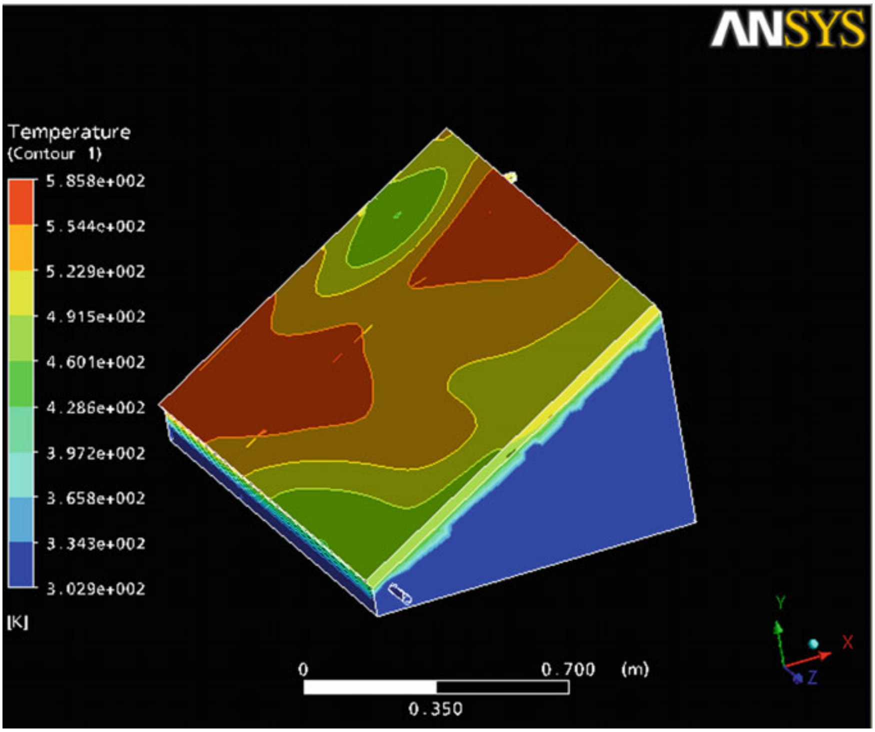


Fig. 40 Distribution of temperature at various points [12]

assumed to be of no slip, and for gas phase, there was slip taken into consideration. In order to increase the effectiveness of the results of the simulation, adiabatic conditions were assumed to avoid loss due to heat transfer. This situation was taken into consideration in the ANSYS. The water level of the still was initially 0.30 for simulation. The water volume fraction was 0.13 and 0.87. The most important factor considered during the simulation was the solar radiation which would initially take place on the glass cover.

3.2 Simulation Results

The mesh made was tetrahedron in shape. For the perfect analysis, the grid size was checked using sizes of 32311, 47126, 64512 and 84121. The more the number of grids, the more the simulation results will be closer to the experimental results.

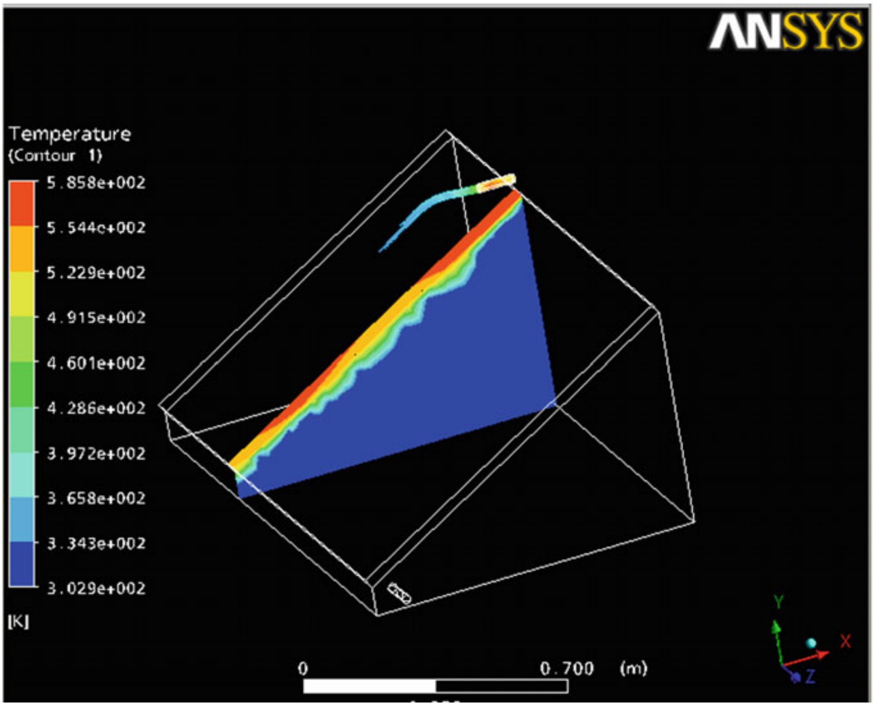


Fig. 41 Side view of the temperature distribution

Figures 40 and 41 give the temperature distribution of the solar still. Since temperature plays an important role in the detailed analysis of the solar still, a detailed simulation of the temperature was done from two different perspectives. The experimental results show that the temperature of the water increases up to 3 p.m. and after that it decreases, which is the main cause of difference in the result of the CFD and the experimental tests. The difference between the experimental and the simulation results is said to be error. This was 6.0 and 10.25% for the amount of fresh water being produced and the temperature of water.

4 Conclusion

The final conclusion can be made that various software have been used for the design and implementation of the solar still. Software such as ANSYS, FLUENT and MATLAB are quite useful tools for the theoretical simulation of various stills. Each of them has a good correlation with the experimental readings, but the benefits of using CFD and MATLAB are it is a time-saving process and year-round performance is not affected. Moreover, these can be used for solving thermal efficiency and heat transfer coefficient using various mass and energy equations. The benefit of using SPSS is that it can be used for solving neural network models and also for finding relation between various parameters. The SPSS also gives a feedback for which neural model is best for use. FORTRAN can be used for finding the effects of radiation of various solar stills using differential equations. The usage, limitations and functions are briefly illustrated in Tables 1, 2 and 3 above according to the various categories of solar still. The software gives an overall idea about how the stills can be modified, what are the parameters which affect the performance of the still, the air flow pattern and the productivity of the various stills. Any scientist or researcher who is interested to make a progress in the area can take into account such software based on one's purpose for further development.

Table 1 Comparison table of various software used in passive solar still (limitations, applications and functions)

S. No.	Software name	Functions	Applications	Limitations
1.	CFD FLUENT/ANSYS	CFD is a simulation software which takes into account the energy, heat transfer and momentum equation and gives the results of temperature, percentage of liquid at various parts, etc. using a pictorial diagram [6–8, 12]	It can be used for finding where the maximum distillations are taking place. Points of modification can be identified and also efficiency can be calculated	Pre-modelling is to be done which is time-consuming. The geometry of the mesh is also a very time-consuming process
2.	MATLAB	MATLAB is a high-performing software which is used for solving all types of mathematical models. It is also used for nonlinear regression analysis [14, 18, 19, 23]	This software is used for making mathematical models to find out the various parameters inside the solar still	Too much stress on the mathematical modelling and hence proper governing equations are to be developed. Moreover, pictorial representation of the process and pattern of outcomes are not represented. Greater stress on programming skills
3.	FORTRAN	It is a computer programming software which can be used for solving mathematical equations using various approximation methods such as the Runge–Kutta method [28, 27]	It is similar to MATLAB, but it takes an array of data for finding out the performance analysis and hourly changes in parameters like changes in water temperature and fresh water output.	A program is to be developed for solving the governing equations which is more or less behaves as mathematical software. Hence too much weightage on programming
4.	SPSS	It is a software used for handling statistical data and for solving ANN network model [26, 25]	It is used for finding the accurate results and various types of results from the data such as the root mean square error and variance analysis	It is quite expensive compared to other software

Table 2 A comparison table of active solar still

S. No.	Software name	Functions	Applications	Limitations
1.	MATLAB	To develop various models for the still taking in account the energy equations [35, 33, 32]	It has its use in solving the energy equations of a still and also finding out the various parameters. An ANN model is also solved	Overall performance evaluation cannot be done
2.	FORTRAN	Used during numerical investigation [37]	Used for solving energy equations and parameters of the still using fourth-order Runge–Kutta method	More weightage on programming rather than calculation and final results

Table 3 Multistage still software comparison chart

S. No.	Software name	Functions	Applications	Limitations
1.	CFD FLUENT/ANSYS	Helps in giving an overall idea of the temperature distributions, path lines of the molecules and the liquid formation rate pictorially. Leading to extensive details about the conditions taking place inside the still [38, 39]	Generally used for finding the heat and mass transfer rates and the energy equations for the still	Not 100% accurate results can be obtained as it fails to take into account f small details such as losses and leakage
2.	MATLAB	Used for solving various numerical models of the still [41, 42]	Used for finding out various coefficients and parameters; this is finally used for carrying out the experimental process	Greater stress on developing proper equations and programming and not the experiment itself
3.	FORTRAN	Used for parameter analysis in various cases or to find out the graphical relation between various parameters [40]	It is limited to the analysis of various parameters in this case	Its domain lies only to the extent of comparison of various parameters

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