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Review

Computational Fluid Dynamic Applications for Solar Stills Efficiency Assessment: A Review

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Abstract: Even though water is a renewable resource, the majority of the available water on the planet is unfit for human use. Moreover, the drinkable water demand is ever-increasing as a result of rising population, urbanization, and life standards, which makes the needs for sustainable, economic, and environment-friendly treatment alternatives of utmost importance. Seawater desalination using solar stills has been proposed as a promising alternative that may help to solve drinkable water scarcity issues. In the past decades, many studies have been conducted to assess the performance of different types of solar stills aiming to enhance their productivity. Computational fluid dynamic (CFD) numerical simulation is one of the approaches that have been used recently to assess the performance of solar stills. The present study performed a systematic review and bibliometric analysis to provide a comprehensive overview of CFD numerical simulation uses as a tool to assess solar stills performance. A total of 486 publications were collected initially from different databases for the period between 2012 and 2022. The collected publications were filtered through several stages reaching 43 publications of highest significance. The collected data were analyzed descriptively, and the bibliometric mapping was presented. Furthermore, the basics and principles of CFD numerical simulation of solar stills efficiency were described and discussed. Later, the previous studies were analyzed to understand the algorithms, methods, and still types used. Finally, future research scopes and conclusions were stated. The presented knowledge in this study can help to provide a deep overview of using CFD in studying the efficiency of solar stills and inspire researchers to identify future research ways and gaps.

Keywords: solar still; computational fluid dynamics; seawater desalination; numerical simulation

1. Introduction

Nowadays, water scarcity is thought to be one of the most important issues all around the world [1,2]. Several factors have contributed to creating and maximizing water shortage issues such as rapid population increment, environmental pollution, urbanization, nation economic progress, changes in land use, and climate changes [3–8]. The United Nations [9] reported that the global population living in urban areas increased from 0.8 billion to 4.4 billion between the years 1950 and 2020. Furthermore, the population of urban areas is expected to reach 6.7 billion by 2050. According to He et al. (2021) [10], one-third of the world population of urban areas (933 million people) was facing water scarcity; this value is expected to increase to nearly half of the global urban population by 2050 (1693–2373 billion people). According to the World Water Assessment Program (WWAP), around 1.10 billion people do not get sufficient potable water, whereas 2 billion people of 40 countries across the world suffer from water shortages [4]. In the future, it is expected that the water shortage issue will become more serious, especially with the climate change issue that has noticeable effects on water availability [11,12].

With the enormous availability of saline water in the seas and oceans, desalination was recognized as one of the most promising alternatives to overcome the water shortage issue and cover the water demand [13]. Consequently, numerous technologies and methods including multi-stage flash (MSF) desalination, multiple effect distillation (MED), thermal vapor compression (TVC), membrane distillation (MD), and reverse osmosis (RO) have been developed [14–16]. However, these techniques use extensive energy and require highly qualified workers and technicians for operations and maintenance [13]. Solar still (SS) is one of the most attractive seawater desalination technologies to produce safe drinkable water [17–19]. It is more economical as it can be fabricated using locally accessible low-cost materials and applies low maintenance and operational cost [20,21]. Besides its economic benefits, solar still is an environmentally friendly technique that can produce freshwater with low carbon dioxide (CO2) emissions [22,23].

The essential concept of the SS is based on evaporation and condensation processes at which sunlight passes through a transparent cover and is absorbed by a black basin filled with salty water. The water heats up and the water vapor condenses on the top of inclined covers, and later the pure water is drained out through the collection channels [24–26]. Three modes of heat transfer occur during the evaporation and condensation processes, including conduction, convection, and radiation. Conduction occurs when the heat flows from inside the solar still to the surrounding environment through the walls and glass cover, while convection occurs while the heat transfers from the basin material to the water. The radiation process exists when the solar heat flows from the sun to the solar still unit [27]. With all the economic and environmental benefits of solar stills, low water productivity remains one of the major challenges that need to be improved and enhanced [28–30].

Over the past years, several experimental, numerical, and analytical studies have been performed to improve the solar still's productivity and various types of stills have been produced [31]. The developed solar still can be categorized into two main types, namely single effect stills and multi-effect stills. Based on the heat sources, these stills can be further classified into active and passive stills [31]. The passive solar still (PSS) is a desalination unit that totally depends on the direct solar energy to heat up the raw water inside the basin, while the active solar still has an external source of heating, such as solar collectors, concentrating collectors, and external and internal heaters [32–34]. An extensive review on solar still types and categorize can be seen in the study by Kumar et al. [31].

The science of computational fluid dynamics (CFD) can be considered as a useful tool to investigate solar still efficiency, especially with its ability to undertake essential analysis on the progress of the physical portions of computer system as well as numerical approaches. However, such studies are limited compared to the published experimental and theoretical investigations [35]. The present work aims to provide a comprehensive review of the most important studies on the CFD approach as a promising tool for studying the performance of solar stills. Systematic and bibliometric analysis assessed the level of achievements using the science of CFD in producing valuable results to enhance solar still research.

2. Methodology

This study aims to provide an extensive overview of using the art of CFD as an alternative and powerful tool to assess the performance of solar stills. The principles and guidelines of the systematic [36] and bibliometric [37] reviews were followed to conduct this study and archive its objectives. In general, a systematic literature review (SLR) is defined as a scientific approach to analyzing, determining, and selecting high-quality literature to come out with concise results [38,39]. On the other hand, to specify the structural, interconnections, and dynamic behavior of scientific research, bibliometric review and mapping can be used [40]. Coupling systematic and bibliometric methods can help to strengthen the outcomes and reduce the weakness of systematic and bibliometric reviews when conducted alone [41]. Therefore, in this study, a mixed method was followed and presented.

In this study, the PRISMA guidelines and scientometric analysis were used to review the previous literature. The process started by defining the scope of the study in which the aim of this study should be achieved at the end of the literature. Afterward, the most appropriate arrangement of the keywords was chosen and designed, with the aim that only the most relevant publications should be collected. Next, several refining processes were conducted to reach the final number of the collected publications. The selected publications were then thoroughly analyzed and discussed. Figure 1 illustrates the detailed description of the methodology adopted in the present study.

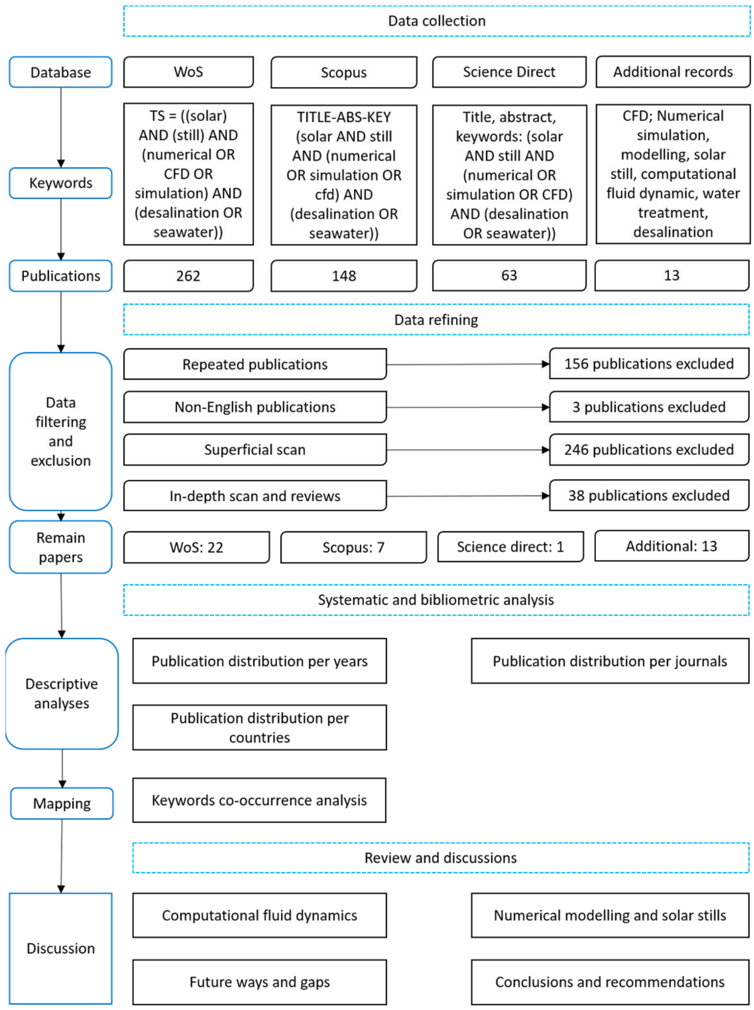

Figure 1. Study flowchart.

2.1. Data Collection

For data collection, the protocol was designed according to the main objectives of this study. The scope was defined to include "solar still", "seawater desalination", "water treatment", "CFD", and "numerical simulation". The relevant publications were taken from the last 10 years (2012 and 2022). Three of the most reliable databases were considered as publication sources, including Web of Science (WoS), Scopus, and Science Direct (SD). Additional related papers published outside these databases were collected from Research Gate and Google Scholar. While searching, different combinations of keywords were designed and developed. Table 1 summarizes the keywords combinations and the terms used and the collected publications from the targeted databases. According to the initial search, a total of 486 publications were collected from journals, conferences proceeding, reviews, and dissertations. Figure 2 presents the yearly distribution of the collected data. It can be noticed that using CFD to study the efficiency of solar stills increased gradually over the past years reaching the maximum by 2021 with a total of 105 publications. Higher numbers of publications are expected in 2022 due to the availability of the advanced CFD tools and solver algorithms.

Table 1. Database, keywords, and the collected publications.

Database	Keywords	Timespan	No. of Publications
Scopus	TITLE-ABS-KEY (solar AND still AND (numerical OR simulation OR CFD) AND (desalination OR seawater))	2012–2022	148
WoS	TS = ((solar) AND (still) AND (numerical OR CFD OR simulation) AND (desalination OR seawater))	2012–2022	262
SD	Title, abstract, keywords: (solar AND still AND (numerical OR simulation OR CFD) AND (desalination OR seawater))	2012–2022	63
Other sources	CFD; Numerical simulation, modeling, solar still, computational fluid dynamic, water treatment, desalination	2012–2022	13

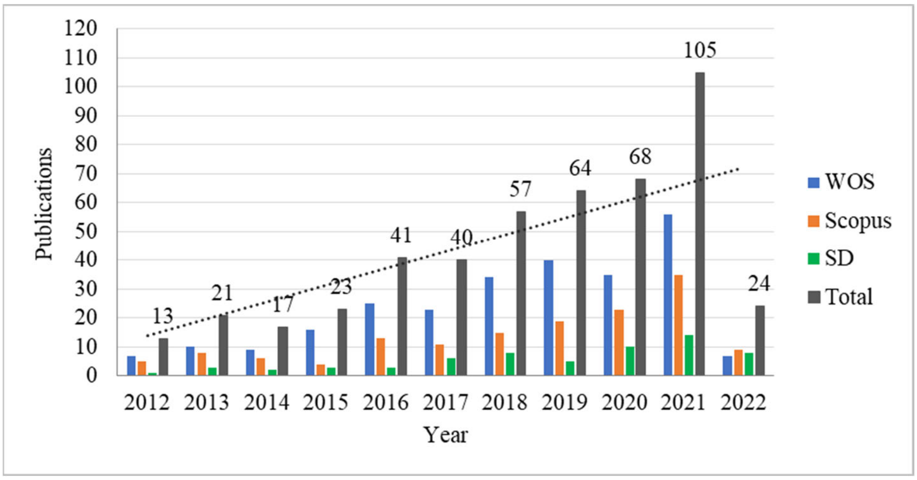

Figure 2. Yearly distribution of the raw collected publications.

2.2. Data Refining

Before conducting reviewing and analysis processes, the collected data underwent different types of filtrations and scanning. The filtration process was performed using the following four steps. The first step excluded the repeated papers, in which the publications with the same titles from the same or different database were not considered. A total of 156 publications were removed. The second step excluded the non-English publications, in which a total of 3 publications were removed. The third step excluded the unrelated publications through the initial screening process; in this stage, only the title and abstract were investigated to check whether the collected publications lie in the scope of the present study. In this stage, a total of 246 publications were removed. The fourth step excluded the reviews and out-of-scope publications through deep screening. Complete manuscripts were evaluated, in which 38 unrelated publications were removed at this stage. Finally, a total of 43 publications meeting the scope were selected for detailed review and analysis. Table 2 summarizes each filtration step and the exclusion process.

Table 2. Summary of components, sub-components, and equipment used at the DWTP.

Databases	Collected Data	Exclusions				
		Common Papers	Other Languages	Initial Screening	Review Papers	Deep Screening
WOS	262	0	2	206	10	22
Scopus	148	98	1	36	5	1
SD	63	58	0	4	0	0
Extra papers	13	0	0	0	0	0
Total Removed	0	156	3	246	15	23
Remain	486	330	327	81	66	43

3. Data Analysis

The collected publications were analyzed under three primary criteria to understand the CFD and solar stills research pattern and its development within the past few years: (i) yearly distribution of the publications, (ii) publication distribution per journal, and (iii) bibliometric mapping of the keywords co-occurrence.

3.1. Yearly Publication Distribution

Figure 3 shows the annual distribution of the collected publications between 2012 and 2022. A smaller number of publications can be observed between the years 2012 and 2019. Around 46.5% (20 articles out of 43) of the total works were published during the first 8 years of the selected period with a maximum publication of five articles in 2018, while highest number (12) of articles were published in year 2020. In addition, it can be noticed that over 53% of the articles were published during the past 3 years (2020–2022), which is higher than the total publications of the previous period (2012–2019). Thus, the use of CFD in studying solar still efficiency has been increasing over the recent years. This was due to the noticeable developments in the numerical approaches and the enormous improvements in the computer's capacity.

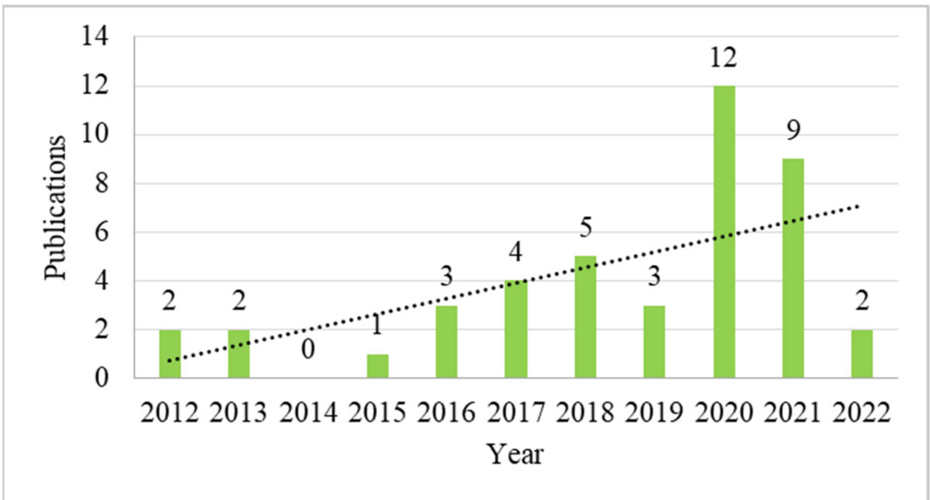

Figure 3. Yearly publication distribution (refined).

3.2. Publication Distribution per Journals

In this study, a total of 29 different sources (journals) were observed from which the refined publications were published. It can be seen that the research topic of evaluating solar stills performance by using CFD approaches is a hot research trend, and several sources are interested to accept and publish related articles. The analysis found that eight sources were published with more than two articles while the rest were published with only one article each. Desalination and Water Treatment Journal published the highest with a percentage of 14.0% (six articles). Desalination Journal ranked second with a publication percentage of 9% (four articles). On the other hand, Energy, Energy Conversion and Management, International Journal of Ambient Energy, IOP Conference Series: Materials Science and Engineering, Materials Today: Proceedings, and Solar Energy published two articles each with a percentage less than 5% and total publications of 12. Other journals published 21 articles with a percentage of 49% as shown in Figure 4.

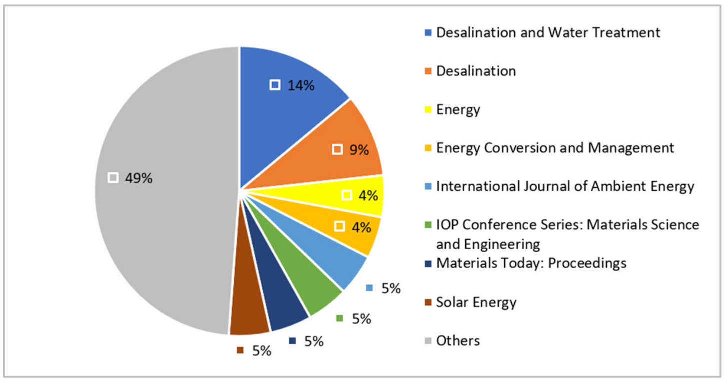

Figure 4. Percentage of articles published per journal.

3.3. Publication Distribution by Locations

Content analysis was used to group the gathered publications based on the study locations and find the geographical locus. It is worth mentioning that several countries are interested to conduct research works on assessing the performance of solar stills using CFD. The collected publications were found to be conducted in 12 different countries across the world. Iran ranked first with a total publication of 13 articles (30%) followed by India with total publications of 12 articles (28%). These observations reveal that the most interesting countries on this research topic are commonly suffering from water shortage issues and have plenty of solar energy during the whole year. China and Egypt published four articles each with a percentage value of 9%. Mexico and Morocco came next with a publication percentage of 5% each (four articles). Other countries including Algeria, Iraq, Jordan, Pakistan, Saudi Arabia, and USA published only one article each, with a total percentage of 14% as shown in Figure 5.

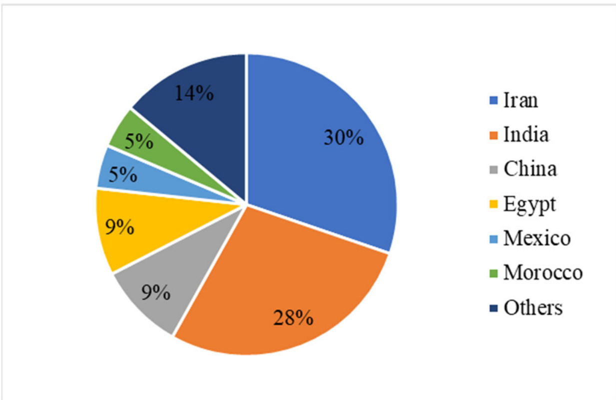

Figure 5. Percentage of articles published per region.

3.4. Keywords Bibliometric Mapping and Analyses

According to Su et al. [42] and He et al. [43], keywords can be used to assist scholars in comprehending mainstream subjects and highlighting potential study areas. Moreover, Eck and Waltman [44] claimed that the research domain knowledge can be demonstrated and displayed through the visualizations and understanding of the keywords' connections. In addition, keyword co-occurrence analysis can help to provide an overview of the research topic's progress over time [45]. In this study, a keywords co-occurrence bibliometric mapping was performed by using VOSviewer software. The minimum frequency threshold of keywords co-occurrence was chosen to be 2. Among the total keywords (130 keywords), only 30 met the designed thresholds which were represented in Figure 6. In Figure 6, the circle and font sizes represent the keyword co-occurrence rate, with a greater size indicating a higher rate of co-occurrence. Different colors represent different clusters at which four clusters can be noticed in Figure 6. Links width represents the strength of the relationship and connections between each keyword at which the connection between terms "solar still" and" CFD" was the highest as can be seen in Figure 6. It was found out that the terms "solar still" and "CFD" are the most common keywords that have been used with co-occurrence rate of 16 and 11, respectively, for the average publication year of 2019. The terms "CFD simulation", "desalination", "solar desalination", and "solar energy" scored next with co-occurrence rate of 8, 7, 5, and 5, respectively. Table 3 summarizes the keywords co-occurrence in terms of tabular form.

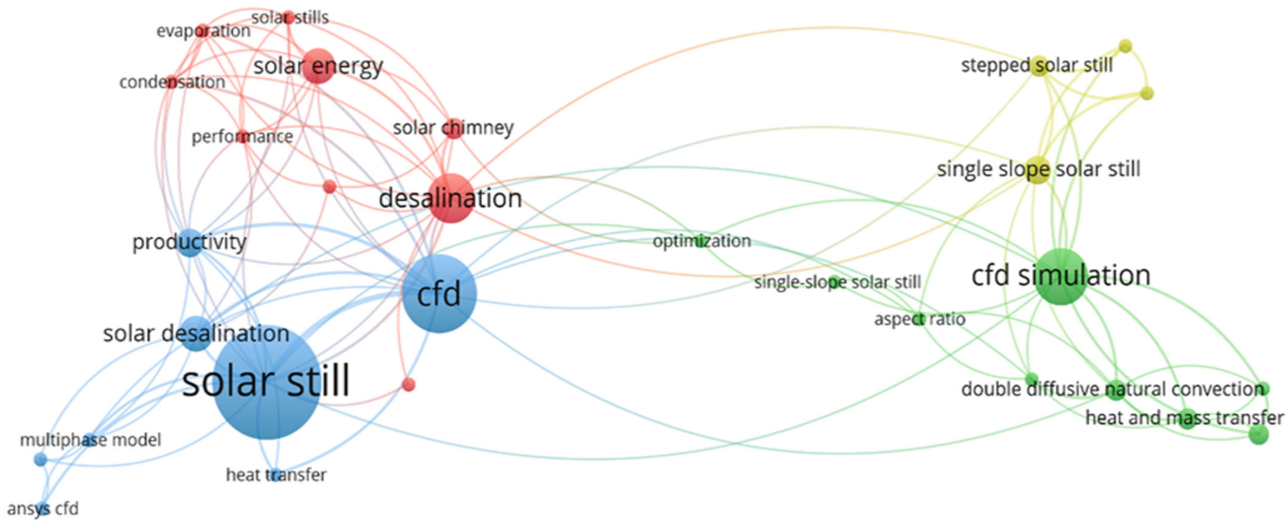

Figure 6. Co-occurrence mapping of author keywords.

Table 3. Details of co-occurring keywords.

Keyword	Total Link Strength	Occurrences	Avg. Pub. Year
Solar still	27	16	2019
CFD	29	11	2019
CFD simulation	21	8	2017
Desalination	18	7	2018
Solar desalination	10	5	2019
Solar energy	11	5	2018
Single slope solar still	13	4	2018
Productivity	14	4	2019
Stepped solar still	10	3	2019
Double diffusive natural convection	11	3	2017
Heat and mass transfer	7	3	2015
Tubular solar still	6	3	2018
Solar chimney	7	3	2018

Table 3. *Cont.*

Keyword	Total Link Strength	Occurrences	Avg. Pub. Year
Parametric study	8	2	2019
Transient model	8	2	2019
Ansys CFD	4	2	2019
Heat transfer	5	2	2021
Multiphase model	7	2	2019
Simulation	4	2	2020
Aspect ratio	5	2	2015
Entropy generation	7	2	2018
Optimization	5	2	2013
Single-slope solar still	3	2	2013
Water productivity	6	2	2017
Computational fluid dynamics	4	2	2021
Condensation	10	2	2018
Evaporation	10	2	2018
Numerical study	2	2	2022
Performance	9	2	2019

4. Computational Fluid Dynamics; Basics and Principles

The art of CFD is a well-known method for analyzing and solving fluid flow issues in a variety of settings. It is a simulation tool that uses applied and computational mathematics to predict heat, mass, and momentum transfer behavior in fluid flow regimes. This analysis, which is based on a simulation procedure, is carried out using computing machines [46]. The accuracy of CFD models has improved in recent years, indicating that CFD is a valid technique for performance analysis and design development for a wide range of thermal-hydraulic systems. This enables researchers to employ it in the simulation of evaporation and condensation processes with a vapor-liquid phase change process, as well as mass and heat transfers, which is one of the most pressing challenges in the development and study of solar stills. CFD is also defined as the analysis of systems, such as fluid flow, heat transfer, and associated phenomena, using computer simulation and numerical investigation to solve mathematical equations. The continuity, momentum, and energy equations, which compose a system of nonlinear partial differential equations, are the governing equations of fluid flow. CFD is a discretization method that uses a set of algebraic equations instead of the differential equations that regulate fluid flow due to the presence of non-linear components. Moreover, there are several discretization methods for CFD; the most utilized methods are the finite difference method (FDM), finite volume method (FVM), finite element method (FEM), and boundary element method [35,47].

Both experimental and CFD methods are commonly used in analyzing the performance of SS, as well as its design and optimization. The CFD technique has numerous advantages over experimental approaches to the design of various fluid systems, including a significant reduction in required time and cost, the ability to investigate systems when experiments are difficult or impossible to conduct (e.g., large systems), the ability to investigate systems under hazardous conditions (e.g., studies for safety and incident purposes), and the ability to provide practically limitless result details. In comparison to experimental work, CFD uses a fairly basic technique to accomplish numerical solutions such as pressure distribution, temperature fluctuations, and flow characteristics in a short period and at a low cost. Various software has been developed in light of the CFD codes that have been implemented, a few of which are: CFDRC-Esi, STAR-CD, CFX, FLUENT, PHOENICS, FLOVENT, and CFDRC-Esi [35].

In general, the processes of conducting numerical simulations to assess SS efficiency in all software are the same. Figure 7 shows a flow chart that illustrates the steps that are commonly followed to conduct the numerical runs. Basically, developing a proper computational grid is the first step to create a numerical model. The grid is comprised of many cells and elements connected to each other in which they represent the original physical domain. The main function of the developed grid is to divide the whole physical domain into smaller volumes for the purpose of solving the fluid governing equations in each grid. Moreover, the unknown parameters values are usually stored in these grids [48,49]. There are several types of computational grids that can be used to develop the numerical models such as tetrahedral, pyramidal, prismatic, and hexahedral (rectangular) grids. Selection of proper grid type is one of the main factors that can help to generate more accurate results and more stable simulations. Beside the grid type, adopting proper grid size is important to produce more accurate results and stable simulations. The second step in creating a numerical model is choosing the solver algorithm that will be used to solve the governing equations. Later, material properties and boundary conditions should be defined accurately to represent the real physical domain. Finally, proper simulation controls such as time steps and iteration numbers should be defined before running the solver [50,51].

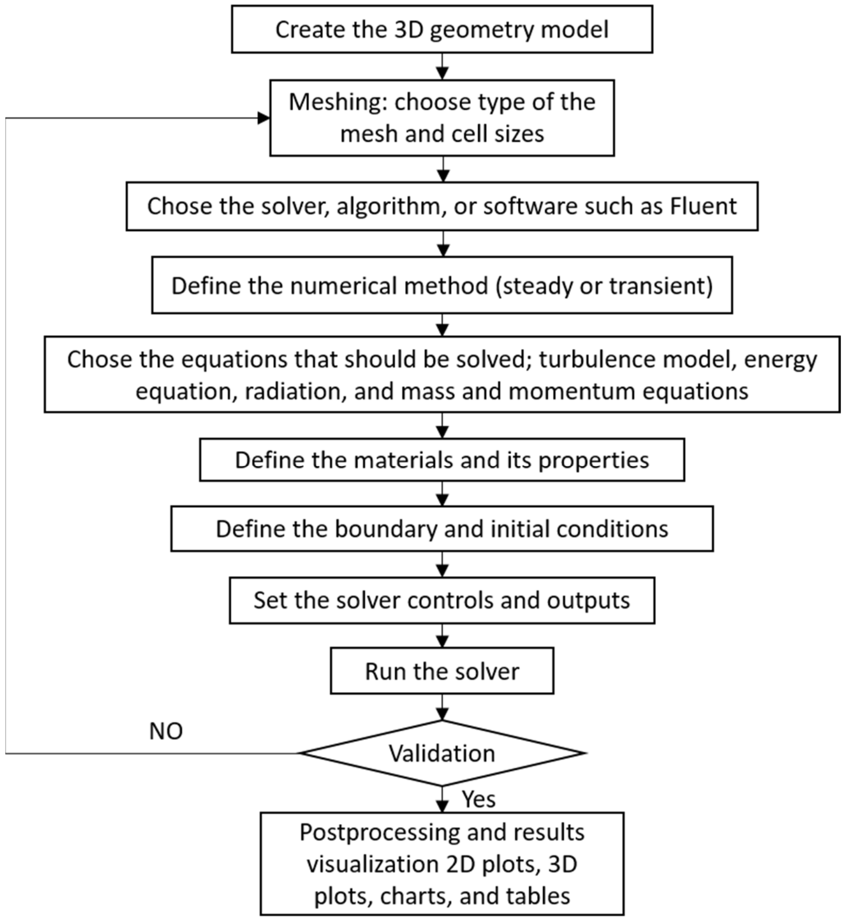

Figure 7. Flowchart of the typical numerical modelling [35].

5. Solar Stills and CFD

Recently, CFD numerical simulations have been widely used to investigate the working mechanism of different solar still systems due to several reasons such as (i) significant reducing time and cost required, (ii) providing more details about the targeted parameters, and (iii) producing results within the complex systems at which the experimental work is hard to be conducted [35]. Hence, many researchers have established using CFD numerical modeling to study the efficiency of solar stills under different climatic conditions and configurations. For instance, El-Sebaey et al. (2020) [13] investigated the performance of single slope solar still experimentally and numerically. Ansys Fluent was used as a CFD tool to conduct the numerical runs. Temperature variations of the glass cover, solar collector, and mixture were presented in 3-D and 2-D renderings at different times during the day as shown in Figure 8. In addition, hourly and cumulative solar still productivity was evaluated and calculated numerically. Later, the numerical outcomes were compared with the experimental investigations and good agreements were observed. A daily efficiency study was performed on the numerical and experimental outcomes, and it was noticed that the numerical daily was higher with a percentage value of 8.3%.

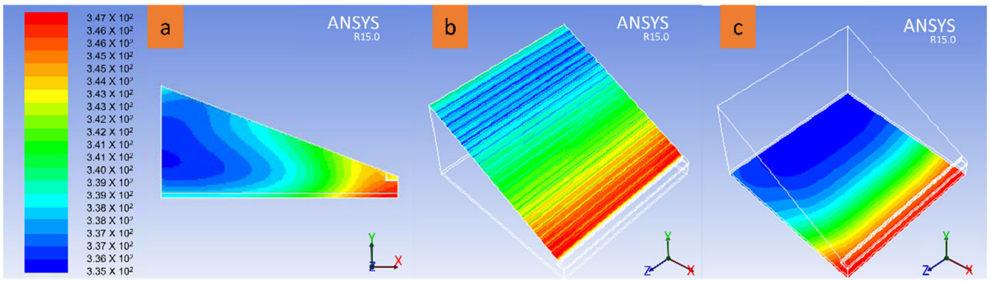

Figure 8. The temperature contours of (**a**) internal mixture, (**b**) glass cover, and (**c**) absorber at 14:00 [13].

Rahbar and Esfahani [52] developed a 2-D CFD numerical simulation model to evaluate the effects of natural convection within a single-slope solar still. Figure 9 shows a simple sketch and configuration of the adopted solar still at which L is the length, H_l and H_r are the lift and right heights, respectively, T_w and T_g are the bottom and top temperature, respectively, g is the gravity, and θ is the glass cover angle. As a result, a new correlation for determining the convective heat transfer coefficient was proposed. In addition, it was reported that the heat transfer coefficient rises as the Rayleigh number increases for a certain aspect ratio (A = L/H) as presented in Figure 10.

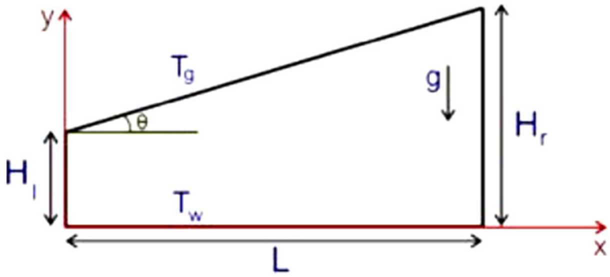

Figure 9. Geometry and coordinate system of the solar still [52].

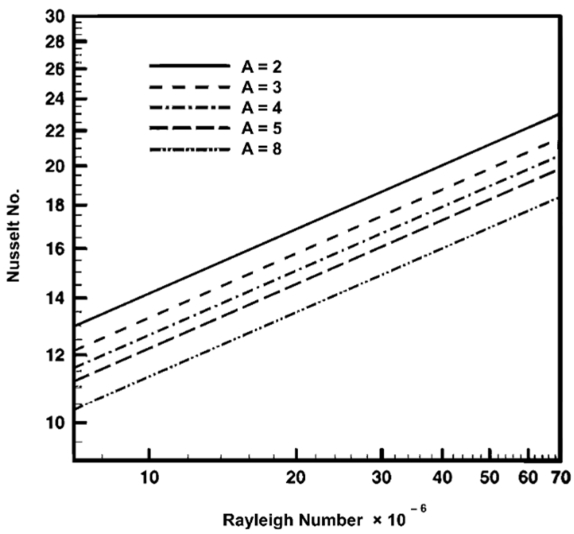

Figure 10. Relation between Rayleigh number and Nusselt number [52].

Rahbar and Esfahani [46] employed the 2-D computational fluid dynamic simulation technique to evaluate the productivity of a single-slope solar still and optimize its geometrical and operating parameters. It was reported that the productivity increases with decrement of the specific height at a fixed length of the solar still. Moreover, it was found that there is an optimum length in which the still productivity is maximized (see Figure 11). Furthermore, it was found that the rise of freshwater productivity follows the trend of the convective heat transfer coefficient (see Figure 11). The obtained results were compared with the results of well-known models of Chiltone-Colburn analogy and Bulk-motion, and good agreement between both results was reported.

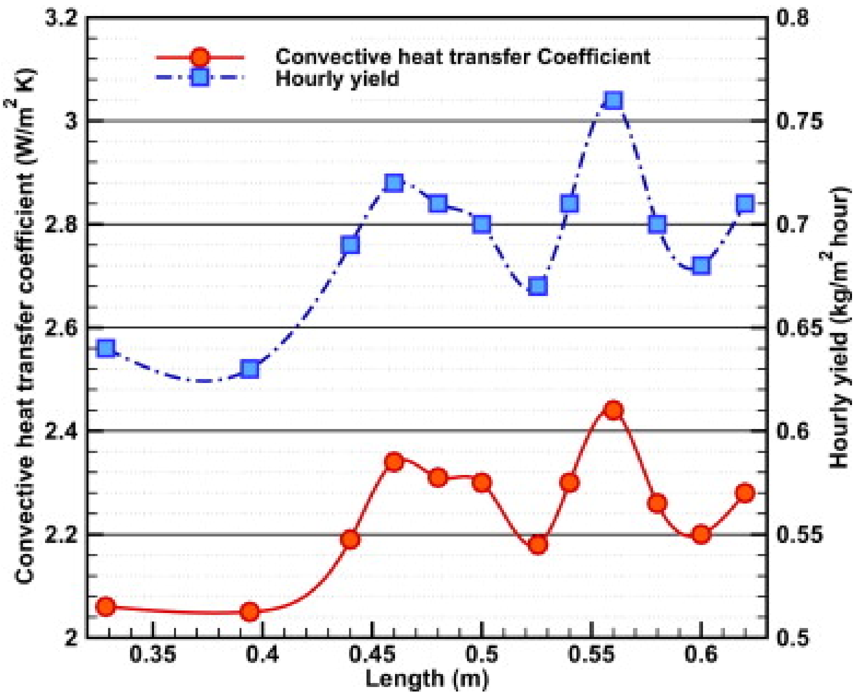

Figure 11. Variation of hourly yield and convective heat transfer vs. length [46].

Double-diffusive free convection and surface thermal radiation of an inclined solar still unit were simulated by Alvarado-Juárez et al. [53]. Finite volume method was employed to solve the 2-D steady-state and laminar flow governing equations. Various angles of the glass cover were tested at which the streamlines, isotherms, isolines of vapor, water mass flow rate, and average Nusselt (Nu) and Sherwood (Sh) numbers were reported. According to the results, it was found that surface thermal radiation varies the fluid flow from a one-cell to a multi-cellular pattern because it increases the velocity near the walls. As a result, the average convective Nusselt number, total Nu, and Sh were all increased by around 25%, 17%, and 15%, respectively. Furthermore, it was noticed that the distillate mass flow rate increases with the increment of the aspect ratio and inclined glass cover angle.

Rahbar et. al. [54] studied the capability of a 2-D CFD simulation technique in predicting the heat and mass transfer in tubular solar still. Figure 12 shows a simple sketch of the adopted model. Based on the obtained results, a novel relationship to estimate tubular solar still parameters (water productivity, heat, and mass transfer coefficients) were introduced. Moreover, a characteristic curve to evaluate water productivity in various operating situations was presented. Furthermore, it was reported that the glass temperature has an inverse influence on the performance of tubular solar still, whereas water temperature has a direct effect as shown in Figure 13. The contours of vapor mass fraction at different values of buoyancy ratio and Rayleigh number were investigated and presented as well (see Figure 14). Rapid changes in vapor mass fraction due to the evaporation and condensation process were observed near to the water surface and glass cover as shown in Figure 14.

Rashidi et al. [55] conducted a 2-D numerical simulation to optimize the position and size of a partition that was proposed to be placed inside a single slope solar still. Figure 15 shows the schematic view of the adopted solar still and its dimensions. A 2-D square mesh was adopted to capture the fluid and solid domains as shown in Figure 16. The mesh was refined close the boundaries where the velocity and other parameters are expected to be changed rapidly. The sensitivity analysis is used to determine the response's sensitivity (Nusselt number) to the partition position and height. Figure 17 shows the contours for several parameters after optimizing the position and height of the proposed partition. It can be seen that installation of partition helps to increase the vortices number in small sizes which provides a sufficient time to heat exchange process and increase the still efficiency. Furthermore, rapid changes in temperature close to the water surface and glass cover can be noticed which was occurred due to the phenomena of condensation and evaporation.

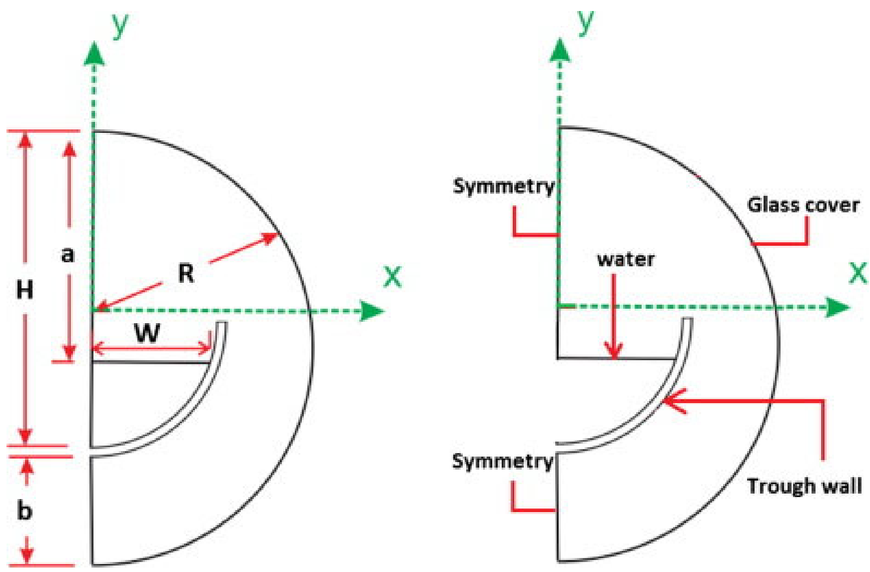

Figure 12. Sketch of the geometry, coordinate system, and boundary conditions of the tubular solar still [54].

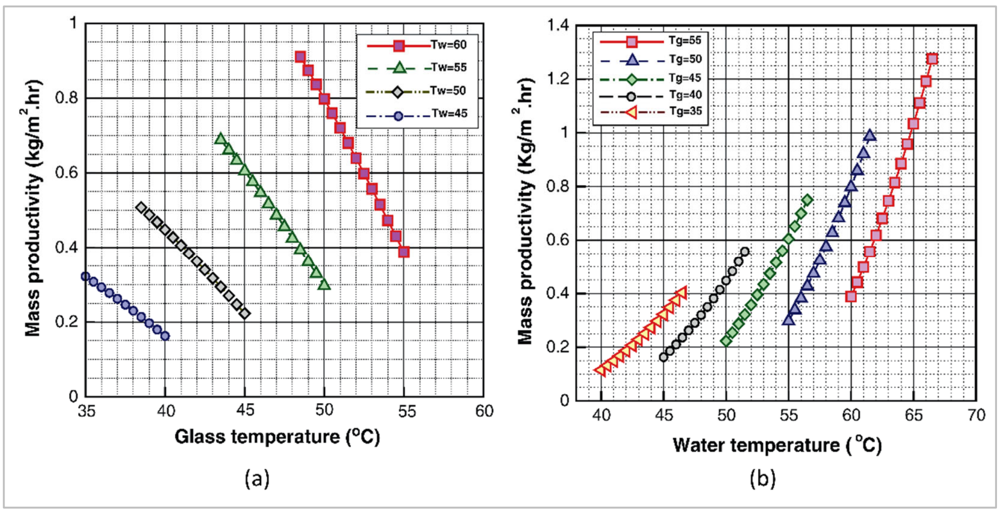

Figure 13. Effects of (**a**) glass temperature and (**b**) water temperature on hourly mass productivity [54].

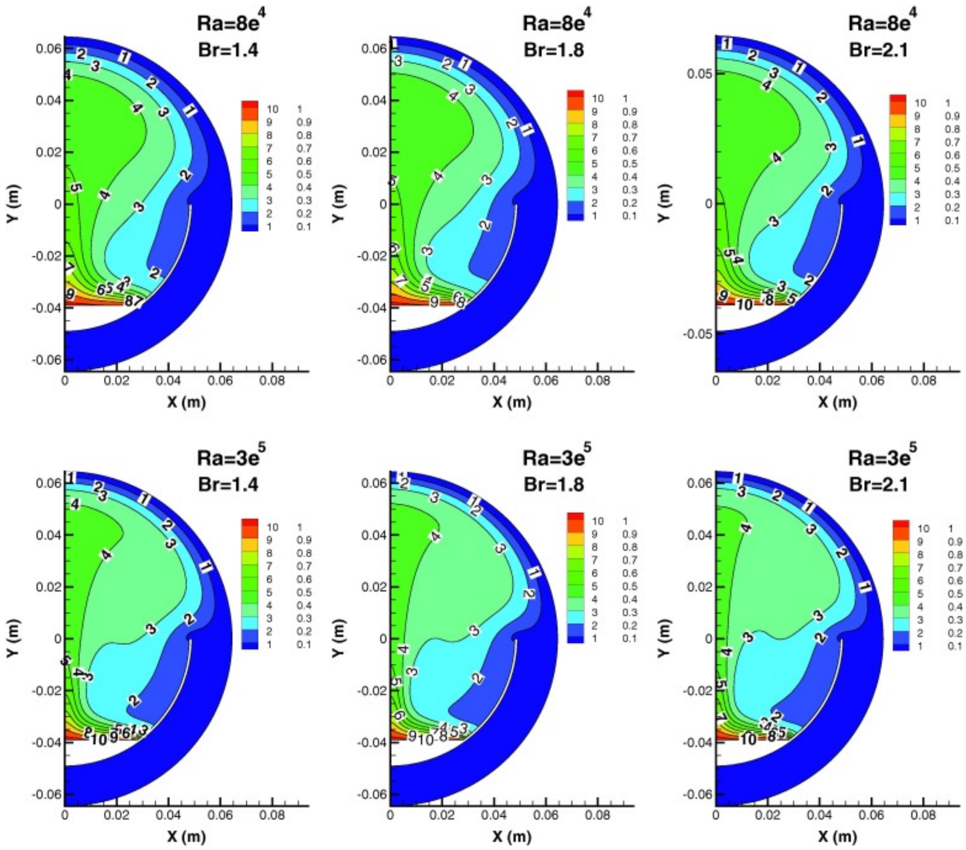

Figure 14. Effect of buoyancy ratio and Rayleigh number on vapor mass fraction [54].

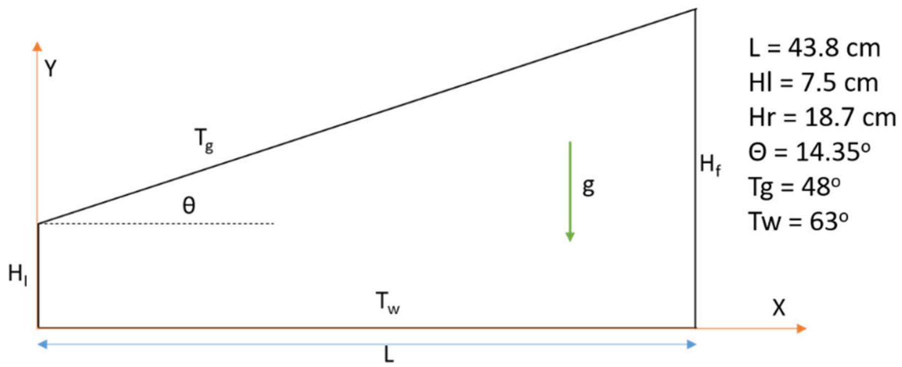

Figure 15. The schematic view of the solar still [55].

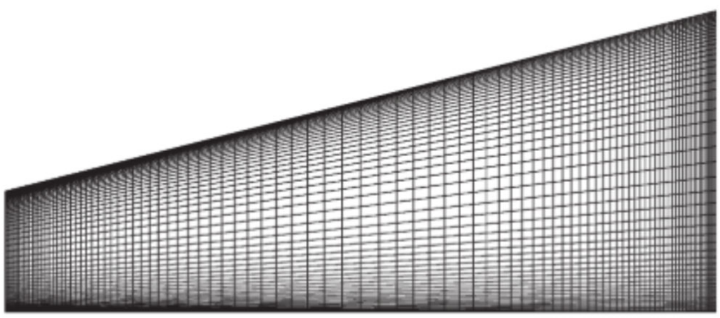

Figure 16. The mesh distribution inside the solar still [55].

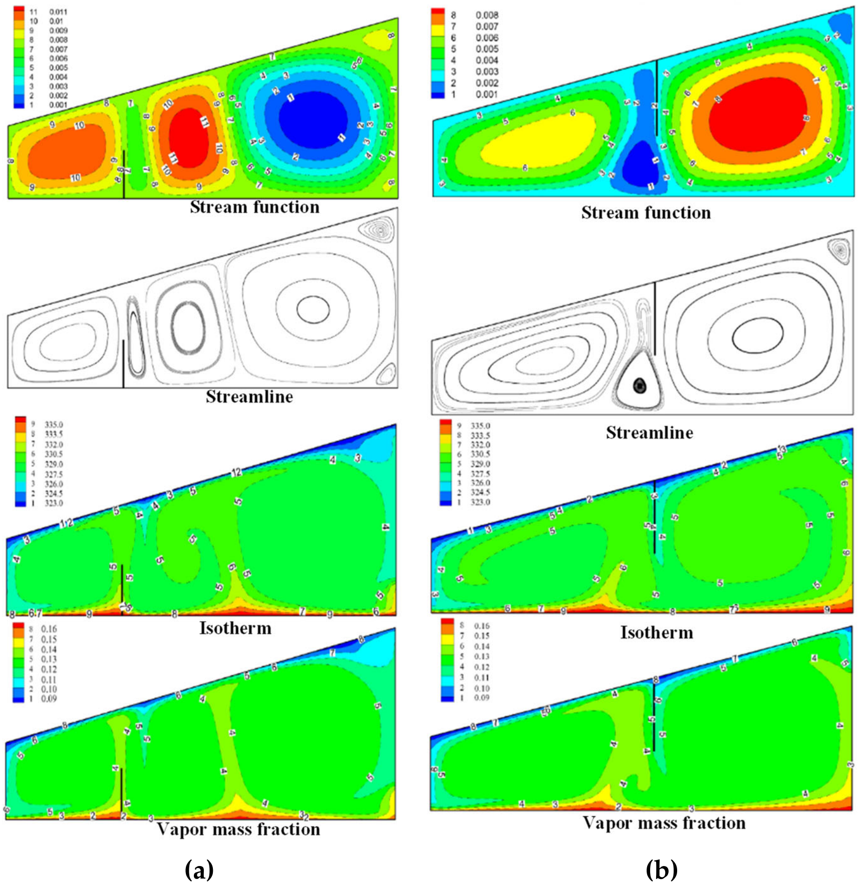

Figure 17. Streamlines, stream function, isotherm, and vapor mass fraction contours [55]. (**a**) still partition at the bottom surface, optimized; (**b**) still partition at the glass cover, optimized.

Using the ANSYS-CFX solver, Malaiyappan and Elumalai [56] performed a 3D numerical analysis based on CFD simulations to investigate the performance of a single slope solar still with three different basin materials, namely galvanized iron, glass, and aluminum. The phase change interactions between water evaporating into vapor at the liquid-gas interface and vapor condensing into water droplets on the top glass surface were represented in their model. Figure 18 shows a comparison between the contours of the liquid water fraction for the three different stills. It was reported that the solar still with the aluminum basin material produced the highest amount of freshwater. A comparison between the obtained numerical results and experimental results was performed and the average errors between both found to be 5.26% under the same boundary conditions as presented in Figure 19.

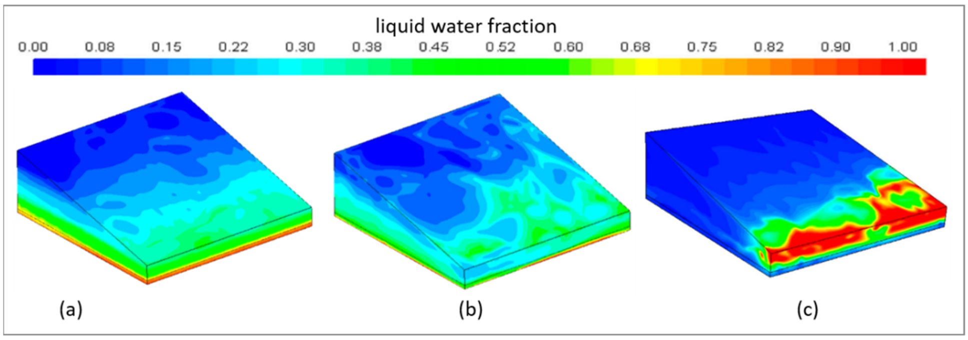

Figure 18. CFD results of liquid water fraction for different basin materials: (**a**) galvanized iron, (**b**) glass, and (**c**) aluminum [56].

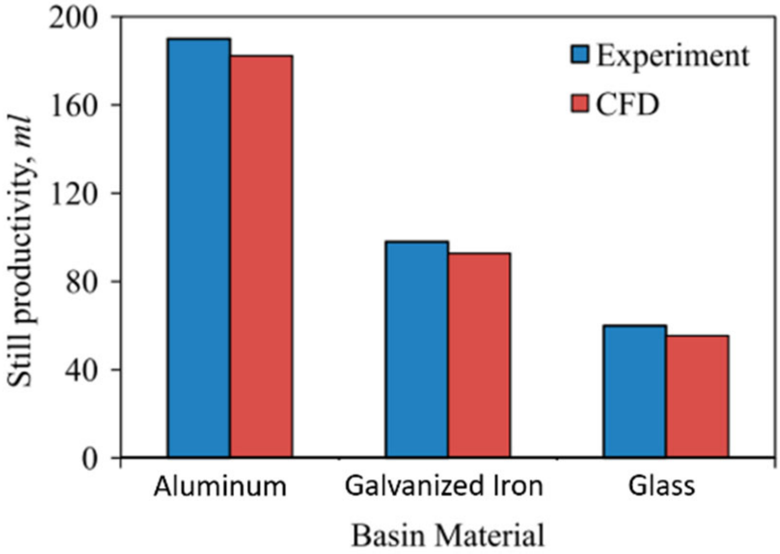

Figure 19. Comparison of water productivity for experimental and CFD results [56].

Using ANSYS FLUENT software, Taamneh [57] developed a 3D two-phase numerical model to study the evaporation and condensation process inside a pyramid-shaped solar still as displayed in Figure 20. Two types of raw water were placed inside two identical pyramid solar stills including Jordanian zeolite-seawater and seawater. Figure 21 shows the hourly water temperature variation for both samples, and it can be seen that the zeolite-seawater temperature was higher during the whole day when compared with normal seawater. Moreover, it was reported that the freshwater that was collected from the still with zeolite-seawater is higher than the freshwater collected from the other still as shown in Figure 22. The obtained numerical results were compared with the experimental results and a good agreement between both were observed.

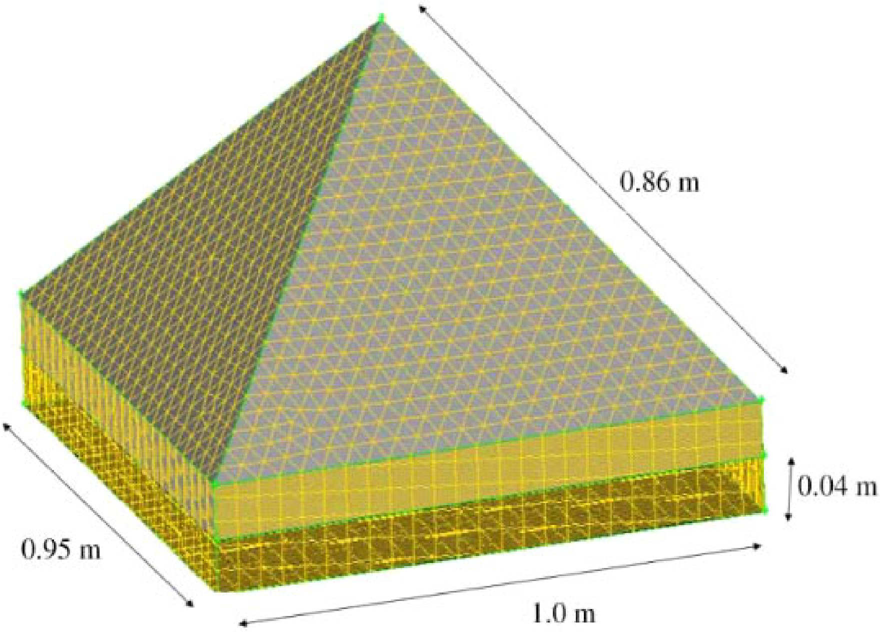

Figure 20. Computational domain and the grid generation using Gambit [57].

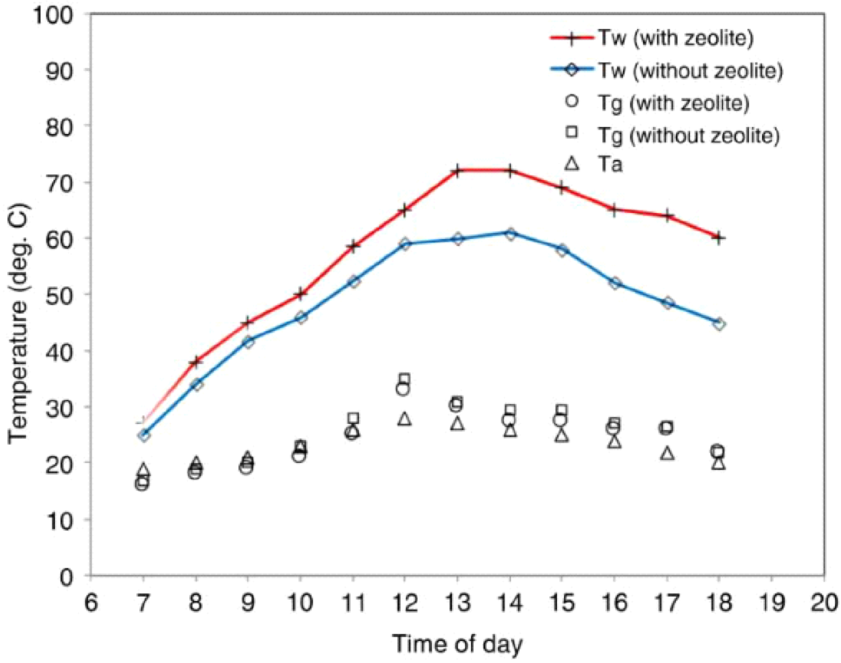

Figure 21. Hourly variation of basin water temperature (Tw), glass cover temperature (Tg), and ambient temperature (Ta) during one day at φ = 0.05 [57].

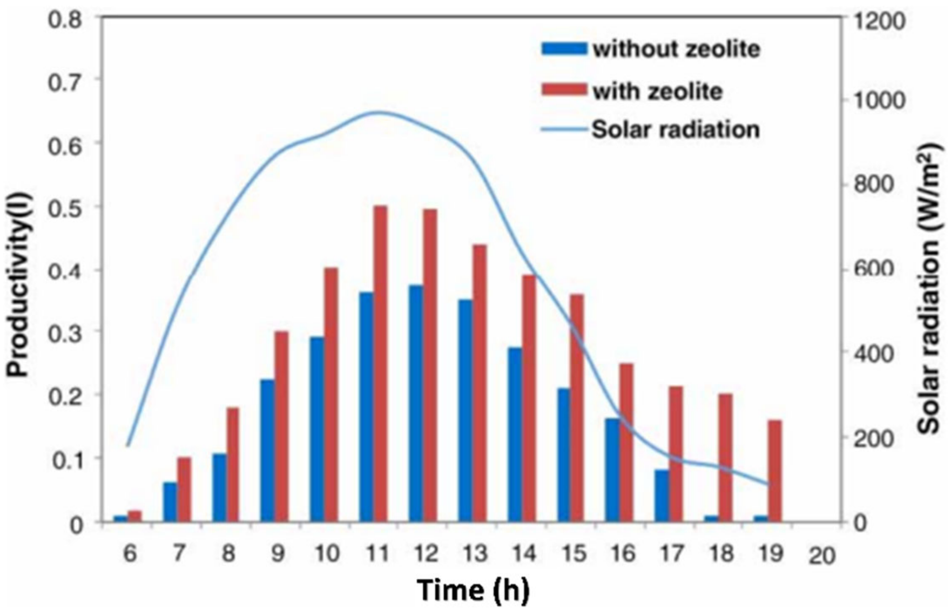

Figure 22. Hourly variation of freshwater production for a solar still filled with and without zeolite at φ $\frac{1}{4}$ 0.05 [57].

Bait and Ameur [58] used SOLIDWORKS and ANSYS FLUENT software to perform a 3D numerical analysis of the geometrical dimensions of a multi-stage solar still in order to track multi-physics evaporation and condensation mechanisms inside the distillation tower (four stages) as shown in Figure 23. The main objective of the analysis was to improve the thermal performance of the solar still system as well as its productivity in order to manufacture it locally. Their parametric investigation has shown that the four-stage distillation system, which is completely isolated from the external medium, can operate at high temperatures of roughly 80.96 °C.

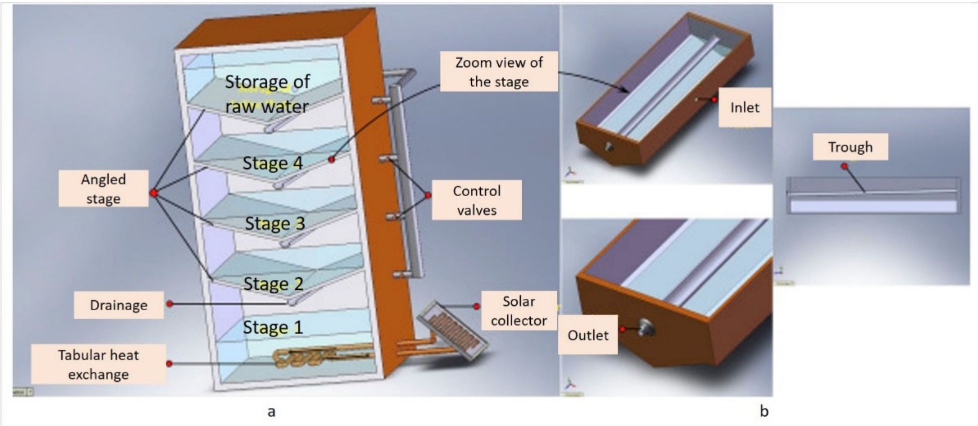

Figure 23. 3D modeling of the multi-stage solar distillation system: (**a**) Major components inside the distillation unit. (**b**) View of a one angled stage [58].

Rashidi et al. [59] used a 2-D computational fluid dynamic simulation to study the impacts of nanofluid on the freshwater productivity of stepped solar still as shown in Figure 24. A sensitivity analysis was utilized to investigate the sensitivity of hourly productivity to step height and length. The shape of the steps inside the still were optimized by utilizing the response surface methodology (RSM). According to the findings, raising nanoparticle concentration from 0% to 5% leads to a 22% increase in hourly productivity. It was concluded that when the stair length is increased for medium and high values of the stair height, the sensitivity of the hourly productivity to the stair height improves, but when the stair length is increased for small values of the stair height, it decreases. Finally, CFD simulation results were compared with RSM results, and the maximum error was found to be 2.4%.

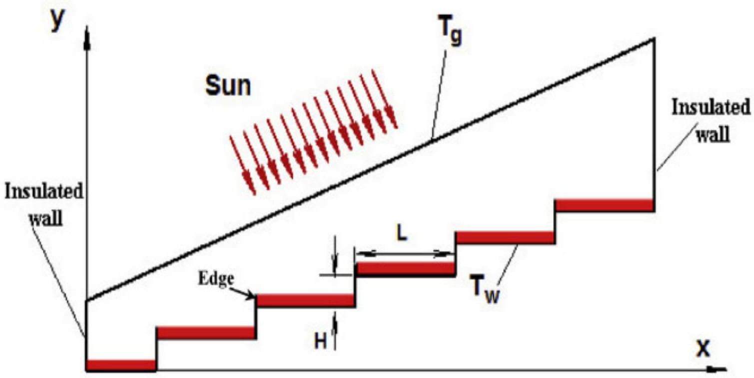

Figure 24. Schematic drawing of the stepped solar still model [59].

Panchal and Patel [60] estimated the performance of a single slope solar still by using a 3-D CFD simulation model through simulating condensation and evaporation processes. An unstructured mesh type tetrahedral was adopted to capture both fluid and solid domains as shown in Figure 25. It was noticed that the temperature reaches to the highest value near to the glass cover as shown in Figure 26. Furthermore, it was reported that the solar still productivity is highly affected by the temperature of the inner glass, outside glass cover, basin water temperature, and vapor temperature. A comparison between experimental and the obtained numerical results was performed in terms of hourly productivity and a good agreement was observed as shown in Figure 27.

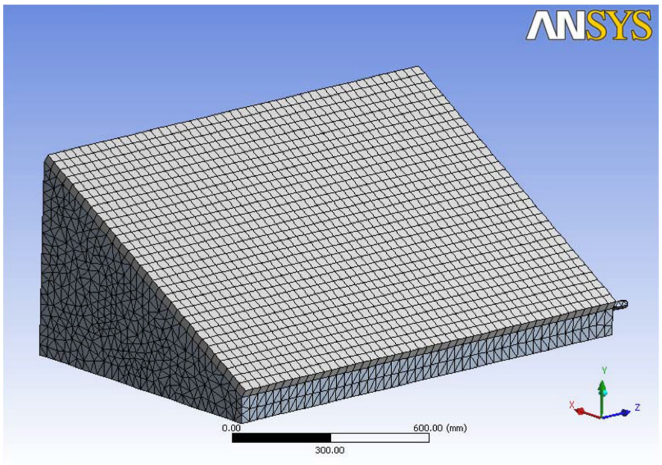

Figure 25. Adopted mesh and solar still geometry overview [60].

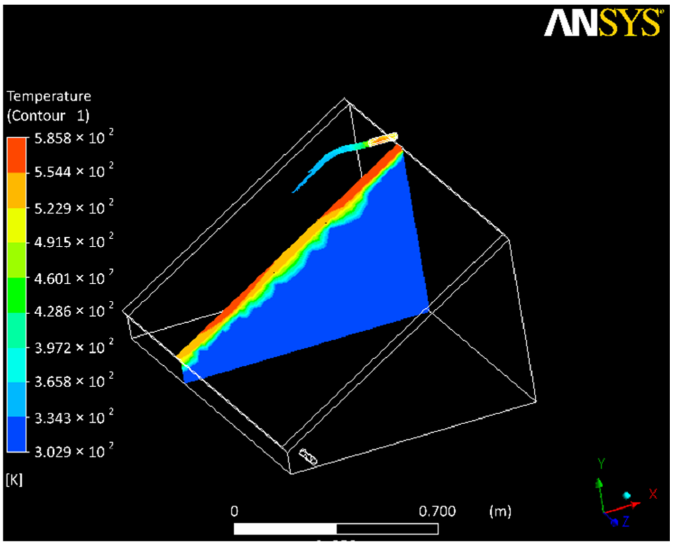

Figure 26. Temperature contours [60].

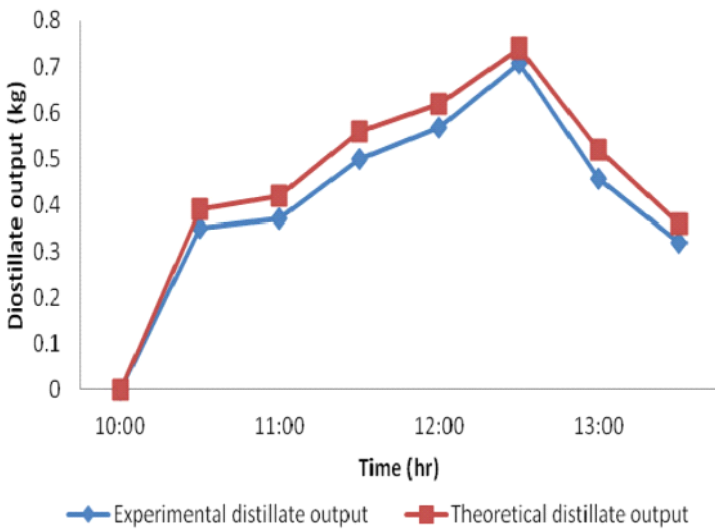

Figure 27. Comparison between experimental and simulation results of the hourly distillate output of the solar still [60].

Arunkumar et al. [61] used CFD modeling to investigate the effect of using carbon impregnated foam (CIF) as a floating absorber with bubble-wrap (BW) insulation material on the freshwater productivity in a single slope solar still (SSSS) desalination unit. The performance of four identical SSSSs was studied under the same environmental conditions as presented in Figure 28. The CIF was permitted to float on the water surface, with a diameter of 170 mm and a thickness of 15 mm. The floating absorbers worked as heat storage, increasing the evaporative surface area of the basin because the CIF was open pore and hydrophilic as shown in Figure 29. According to the results, it was noticed that the freshwater productivity of the SSSS without insulation and with BW insulation were 1.9 L/m^2/day and 2.3 L/m^2/day, respectively, whereas the productivity was better (3.1 L/m^2/day) when using SSSS-CIF with BW insulation. A conventional solar still with sawdust insulation achieved a daily productivity of 2.2 L/m^2.

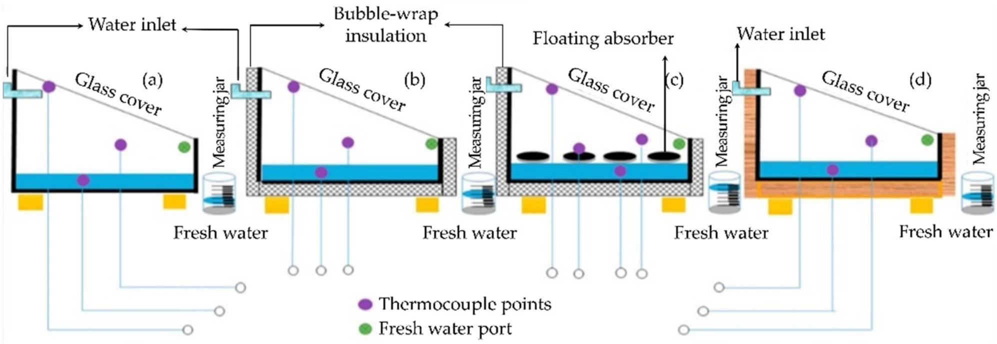

Figure 28. (**a**) SSSS without insulation, (**b**) SSSS with BW insulation, (**c**) SSSS-CIF with BW insulation, and (**d**) Conventional solar still [61].

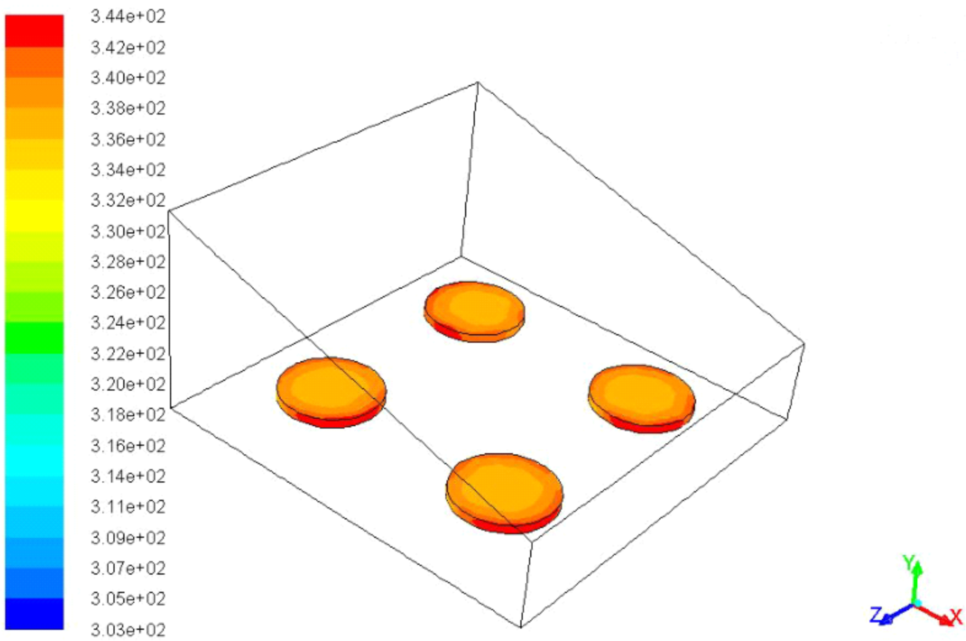

Figure 29. Temperature distribution in Kelvin of the floating absorber in the solar still [61].

Rahbar et al. [62] conducted experimental and CFD modeling to study the influence of geometry on the performance of triangular and tubular solar stills as shown in Figure 30. Second law analysis is used to estimate the local entropy generation inside the cavity of these solar stills. The results showed that the tubular had a 20% advantage over the triangular in terms of performance. Furthermore, simulation results demonstrated that the stronger recirculating zones and reduced entropy generation are the major reasons for the tubular still producing more freshwater as presented in Figure 31. In addition, life cost analysis was used to estimate the cost of generated freshwater. As a result, two correlations were given to forecasting the solar stills' efficiency and production under diverse weather conditions.

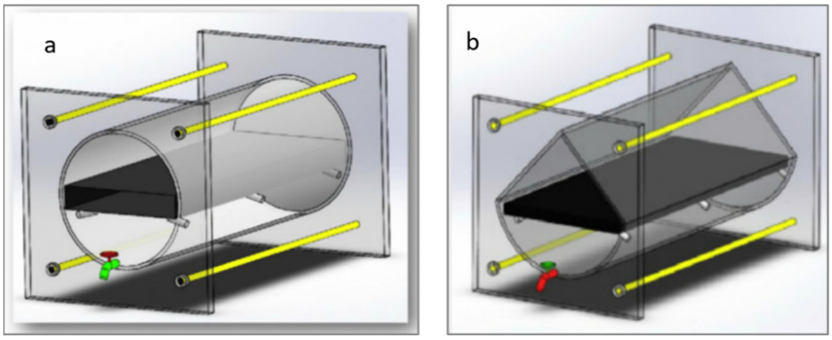

Figure 30. Schematic drawing of (**a**) the tubular solar still and (**b**) the triangular solar still [62].

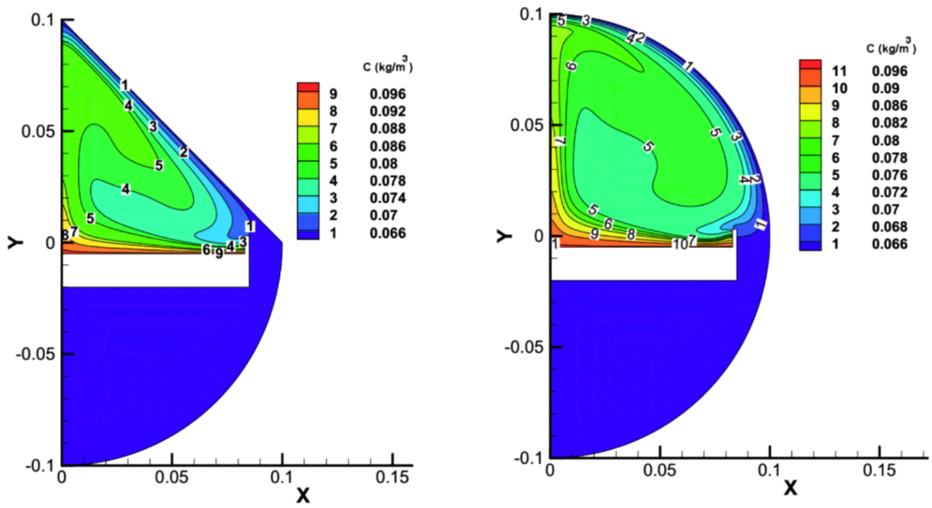

Figure 31. Mass fraction in tubular and triangular solar stills (Tw = 325 K, Tg = 318.5 K) [62].

Maheswari and Reddy [63] conducted an experimental and CFD numerical study to evaluate the efficiency of six different configurations of solar stills including single slope solar still with 15° cover angle, single slope solar still with 20° cover angle, steps solar still, fins solar still, single slope solar still with phase modification materials (PCM), and double slope solar still. A tetrahedral mesh was generated for each type of solar still as shown in Figure 32. Water mass fraction was analyzed, and the 2-D and 3-D contours were generated for all the simulated models. It was found that the productivity of the single slope solar still with a 20° cover angle and integrated with PCM is the highest when compared to other types.

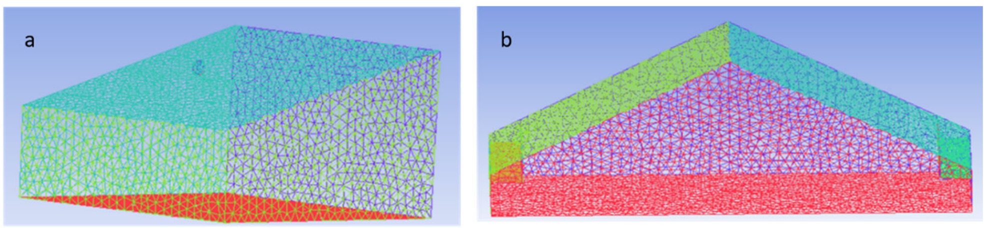

Figure 32. Generated mesh for different types of solar stills [63]. (**a**) generated mesh for 15°,20°, fine, steps, PCM solar stills; (**b**) generated mesh for double slope solar still.

Tiantong et al. [64] used CFD modeling to investigate the effects of operating pressure *Pop* and geometrical parameters on the efficiency of a tubular solar still (TSS), with an emphasis on vapor flow in the enclosure. Figure 33a,b show the general overview of the adopted solar still geometry and the computational fluid mesh domain, respectively. Tiantong et al. [60] reported that vacuum operation led to higher humid air-flow velocities and greater water vapor mass diffusion within the TSS as shown in Figure 34. At operating pressures less than 60 kPa, the freshwater yield rate was enhanced by more than 50% as displayed in Figure 35. In addition, they show that the yield rate was observed to decrease as the water depth and radius ratio (r/R) decreased. Its value was reduced by 30% when the water depth was reduced from r to 0.8 r, and by 38% when the radius ratio (r/R) was varied from 0.6 to 0.9 at an operating pressure of 20 kPa.

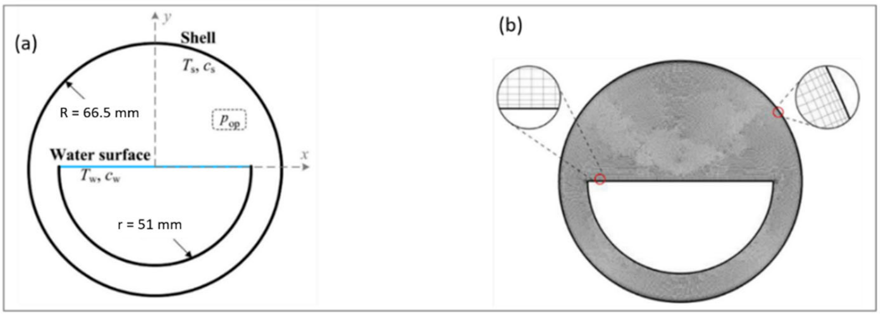

Figure 33. The Tubular Solar Still (TSS): (**a**) Sketch of the geometry, boundary, and operating conditions, and (**b**) the mesh of the computational domain [64].

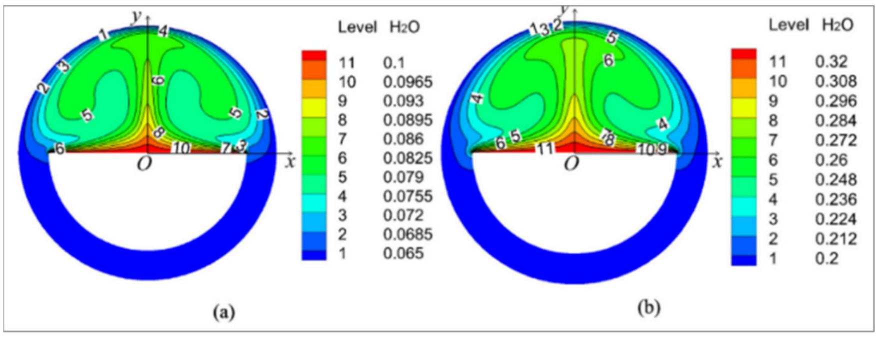

Figure 34. Contours of vapor mass fraction at Tw = 60 °C and Pop of (**a**) 101 kPa and (**b**) 40 kPa [64].

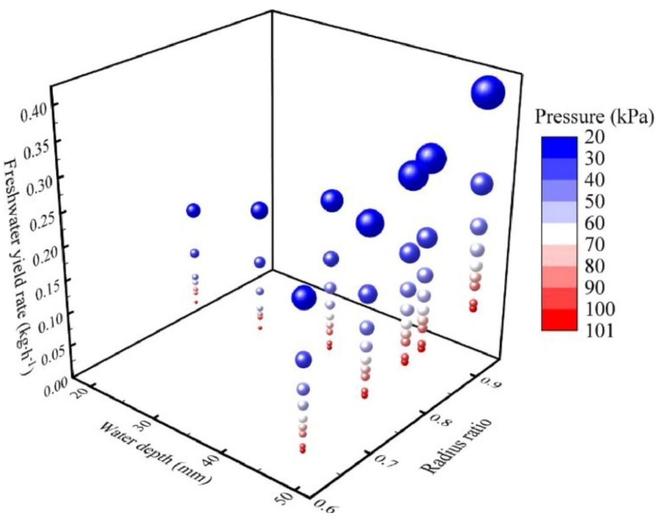

Figure 35. Effect of the water depth (Dw) and radius ratio (i = r/R) on freshwater yield rate of the TSS [64].

Table 4 summarizes the most common studies that have been published investigating solar still efficiency using the CFD approach. Based on the table it can be seen that the efficiency of almost all solar still types such as single slope, double slope, pyramid, etc. can be studied and analyzed using CFD. Moreover, several parameters can be investigated and visualized using the powerful tools of CFD numerical modeling such as raw water temperature variation, fluid and vapor fraction, productivity, mixture velocity, heat, mass transfer coefficients, and solar still components temperatures. 2-D and 3-D contour rendering can be presented and introduced as well to provide a close look at the evaporation and condensation process and the temperature variations with time for each solar still component. Ansys fluent and Ansys CFX with the advantage of the Volume of Fluid (VOF) function was found to be the most common software that has been used in the previous studies which makes it the most recommended CFD tool when conducting future analysis. Furthermore, comparisons between the CFD results and experimental results were performed. According to Table 4, it was found that the differences between experimental and CFD numerical approaches are small and neglectable.

Table 4. Summary of the research work on solar still systems using CFD approach.

Approaches	Still Type	Software	Discretization Method	Water Depth	Multiphase Model	Validation	Studied Parameters	Productivity/Performance	Reference
Experimental and numerical	Single slope (SS)	Ansys Fluent	FVM	2 cm	Volume of fluid (VOF); three phases	Yes. The error is 8.3%.	Temperature's variation, fluid and vapor fraction, productivity, and mixture velocity contours	Daily simulated and experimental cumulative freshwater productivities were to be 1.982 and 1.785 L/m^2 h, respectively.	[13]
Experimental and numerical	Cascade solar still	Ansys Fluent	FVM	NA	Volume of fluid (VOF); three phases	Yes	Absorber plate temperature, hourly productivity, and solar intensity variations	The absorber plate temperature and freshwater productivity can reach more than 60 °C and 1.66 kg/m^2 h, respectively.When the absorber plate temperature is over 50 °C, the freshwater productivity may reach 0.6 kg/m^2 h.	[65]
Theoretical and numerical analysis	Single slope (SS)	Ansys Fluent	FVM	NA	Volume of fluid (VOF); three phases	The theoretical results have a maximum deviation of 12.5% from the numerical results.	The convective heat transfer coefficient, Rayleigh number, and still geometry (aspect ratio = length/height)	It was reported that the heat transfer coefficient rises as the Rayleigh number increases for a certain aspect ratio (A = L/H).	[52]
Theoretical and numerical analysis	Single slope (SS)	Ansys Fluent 6.3	FVM	NA	Volume of fluid (VOF); three phases	Yes. The maximum deviation of the CFD model from Chiltone Colburn for the hourly productivity is 15%.	Variation of thermal conditions (water and glass temperatures) and geometry parameters (height, length, and inclination angle)	The freshwater productivity is increasing with decreasing the specific height at fixed length of the solar still.There is an optimum length for the solar still to increase the freshwater productivity at fixed specific height.	[46]
Numerical analysis	Single slope (SS)	Ansys Fluent	FVM	NA	Volume of fluid (VOF); three phases	- In case of the buoyancy ratio (N), the maximum error is 2.1% for N = −0.9 compared with literature.- In case of the convective, radiative and total average Nusselt number, the maximum error is 2.8% compared with literature.	Streamlines, isotherms, and isolines of vapor and water mass flow rate, as well as average Nusselt (Nu) and Sherwood (Sh) numbers for different inclination angles	As the slope angle, Rayleigh number, or aspect ratio rises, the freshwater productivity rises as well.	[53]

Table 4. *Cont.*

Approaches	Still Type	Software	Discretization Method	Water Depth	Multiphase Model	Validation	Studied Parameters	Productivity/Performance	Reference
Theoretical and numerical analysis	Tubular solar still	Ansys Fluent 14.0	FVM	NA	Volume of fluid (VOF); three phases	At certain value of the convective heat transfer coefficient between water and glass cover, the estimation accuracy is 10% compared with experimental data reported in literature.	Water productivity, heat, and mass transfer coefficients at different water and glass temperatures	Productivity increases by more than 250% even with a 5 °C increase in water temperature.While the temperature of the glass just rises by 5 °C, productivity is reduced by almost 200%.	[54]
Numerical analysis	Single slope (SS)	Ansys Fluent	FVM	NA	Volume of fluid (VOF); two phases	There is a high level of agreement between the results of this study and the previously published data.	Position and height of the partition on heat transfer rate and productivity	It is found that the partition height has a greater impact on heat transfer rate and freshwater productivity rather than the partition position parameter.	[55]
Numerical and experimental analysis	Single slope (SS)	Ansys CFX solver	FVM	2 cm	Volume of fluid (VOF); three phases	The average errors in CFD for the same boundary conditions as the experiment are 5.26%.	Production using three different basin materials (galvanized iron, glass, and aluminium)	It was found that the solar still with aluminum basin material achieves the highest freshwater productivity, followed by the galvanized iron basin material, and then the glass basin material, which is the least of them in productivity.	[56]
Experimental and numerical	Pyramid shaped solar still	Ansys Fluent	FVM	4 cm	Volume of fluid (VOF); two phases	With increasing zeolite particle volume fraction, the deviation of CFD model from experimental data rises (0.05% for $\varphi = 0.0$ and 12.3% for $\varphi = 0.05$).	Basin water temperature, freshwater productivity, water vapor fraction, and velocity counters	The freshwater productivity can be enhanced by adding zeolite particles.	[57]
Design and numerical analysis	Multi-stage solar still (four stages)	Solidworks and Ansys Fluent	FVM	NA	Volume of fluid (VOF); three phases	NA	Temperature and freshwater productivity as a result of thermal radiation term exchange	The four-stage distillation system can operate at high temperatures of roughly 80.96 °C and achieve high freshwater productivity (8.88 kg/day for all stacked stages).	[58]

Table 4. *Cont.*

Approaches	Still Type	Software	Discretization Method	Water Depth	Multiphase Model	Validation	Studied Parameters	Productivity/Performance	Reference
Numerical analysis	Stepped solar still	Ansys Fluent	FVM	NA	Volume of fluid (VOF); two phases	In compared to the CFD simulation, RSM accurately predicts freshwater hourly productivities with a maximum error of 2.4%.	Percentage of nanoparticles, stepped solar still geometry (length and height), and freshwater hourly productivity	It is shown that raising nanoparticle concentration from 0% to 5% leads to a 22% increase in hourly productivity.When the stair length is increased for medium and high values of the stair height, the sensitivity of the hourly productivity to the stair height improves, but when the stair length is increased for small values of the stair height, it decreases.	[59]
Numerical and experimental analysis	Single slope (SS)	Ansys Fluent 11	FVM	3 cm	Volume of fluid (VOF); two phases	The simulation and experimental results are quite close.	Freshwater productivity, temperature of the inner glass, outside glass cover temperature, basin water temperature, and vapor temperature	It is found that the freshwater productivity is affected by the temperature of the inner glass, outside glass cover temperature, basin water temperature, and vapor temperature.	[60]
Numerical and experimental analysis	Single slope (SS)	Ansys Fluent 15	FVM	3 cm	Volume of fluid (VOF); three phases	The simulation results of the CFD show a good agreement with the experimental results.	Water temperature, internal air temperature, inner core temperature, carbon impregnated foam temperature, and freshwater productivity	The freshwater productivity of the SSSS without insulation, SSSS with BW insulation, SSSS-CIF with BW insulation, and conventional solar still with sawdust insulation, respectively, was 1.9 L/m^2/day, 2.3 L/m^2/day, 3.1 L/m^2/day, and 2.2 L/m^2/day.	[61]
Numerical and experimental analysis	Triangular and tubular solar stills	Ansys Fluent	FVM	NA	Volume of fluid (VOF); three phases	The comparison of the CFD results revealed a maximum error of 6.1% from the experimental results.	Contours of streamlines, isotherms, mass fraction, and local entropy generation inside the solar stills	It is found that the tubular had a 20% advantage over the triangular in terms of performance.	[62]

Table 4. *Cont.*

Approaches	Still Type	Software	Discretization Method	Water Depth	Multiphase Model	Validation	Studied Parameters	Productivity/Performance	Reference
Theoretical, numerical and experimental analysis	Single slope (SS), double slope (DS), stepped, finned and PCM solar stills	Ansys CFX	FVM	5 cm	Volume of fluid (VOF); two phases	There is a high level of agreement between the simulation and experimental results.	Temperature distributions of water and vapor, and freshwater productivity at 15 and 20 inclination angles of solar stills	It is established that a single slope with a 20° angle and PCM equipment yielded the highest freshwater productivity when compared to other types.	[63]
Numerical and experimental analysis	Tubular Solar Still (TSS)	Ansys Fluent 16	FVM	2 cm	Volume of fluid (VOF); three phases	The average and maximum deviations between the experimental and simulated yield rates are 14.1% and 32.4%, respectively.	Operating pressure *Pop* and geometrical parameters (radius ratio and water depth) on freshwater productivity	At operating pressures less than 60 kPa, the freshwater yield rate was enhanced by more than 50%.The freshwater yield rate reduced by 30% when the water depth was reduced from r to 0.8 r, and by 38% when the radius ratio (r/R) was varied from 0.6 to 0.9 at operating pressure of 20 kPa.	[64]
Numerical and experimental analysis	Single slope solar still (SS)	Ansys Fluent	FVM	5–15 L water	Three phases	In case of the convective, radiative, and total average Nusselt number, the maximum error is 2.8% compared with literature.	Water depth, materials of basin, and radiation intensities	With less water depth, freshwater productivity is increased.By adding a blackened baseliner to the basin and using reflecting glasses to maximize incident solar radiation, the still's efficiency is further improved.	[66]
Numerical analysis	Single slope solar still (SS)	ANSYS 17.1, CFX	FVM	NA	NA	Yes, 0.6–14% difference is found between experiments and CFD model's output.	Internal temperature, productivity, and transfer coefficient	The radiation is the main factor in high efficiency, although freshwater productivity can also be impacted by wind speed and ambient temperature.	[67]
Numerical and experimental analysis	Single slope solar still (SS)	Ansys Fluent	FVM	NA	Three phases approach	Yes. The difference between experimental and numerical approaches is 8.7% in terms of daily productivity.	Design parameters on performance of a solar still	The produced water volume found to be 1.03 L which was collected between 9 AM and 5 PM.	[68]

Table 4. *Cont.*

Approaches	Still Type	Software	Discretization Method	Water Depth	Multiphase Model	Validation	Studied Parameters	Productivity/Performance	Reference
Numerical analysis	Single slope solar still (SS) and tubular solar still	Ansys Workbench	FVM	2 cm	VOF -two dimensional	The variation ranges from 2.8 to 0.95% between experimental and CFD studies.	Analyzing the effectiveness of each design and considering the impact of temperature variations caused on by modifications to the basin's geometry.	The curved water basin should be at 1/2 of the still's diameter for higher Rayleigh numbers for the solar still to function well. The tubular still with a linear basin at D/2 dissipates 31.4% more heat than conventional stills (SS). This results in a higher rate of solar still fresh water productivity at higher Rayleigh numbers.	[69]
Numerical and experimental analysis	Single stepped slope solar still	Ansys Fluent	FVM	1–4 cm	VOF	Very good agreement between the numerical model and experimental data.	Wind speed, glass cover thickness, water depth, water to cover distance, and cover inclination.	When the wind speed is increased from 1 m/s to 6 m/s, productivity increases by 14.4%, and when the glass thickness is decreased from 4 mm to 2 mm, productivity improves by 3.5%. While the cover tilt is equal to the angle of the local latitude, the ideal values of water depth and water to cover distance are identified to be 2 and 8 cm, respectively. Moreover, freshwater productivity rises by roughly 17.4% when the basin solar still is changed to the suitable stepped solar still.	[70]
Numerical and experimental analysis	Double slope solar still (DSSS)	ANSYS Fluent	FVM	N/A	Three-dimensional	The simulation results deviate from 5 to 13%.	Glass cover temperature, surface water temperature, basin temperature, ambient temperature, and solar intensity	While a CFD modeling result shows 0.50 $L/m^2/day$, experimental investigation indicates that the total amount of distilled water is around 0.46 $L/m^2/day$. Therefore, there is good agreement between the simulated findings and the experimental distillate yield data.	[71]

Table 4. *Cont.*

Approaches	Still Type	Software	Discretization Method	Water Depth	Multiphase Model	Validation	Studied Parameters	Productivity/Performance	Reference
Numerical analysis	Axisymmetric shape column solar still	FLUENT	PRESTO	N/A	Three-phase three-dimensional model	NA	Pressure, velocity, and temperature of the integrated system	After the geometric dimensions are optimized, the airflow characteristics in the collector minimally change, thus the freshwater productivity in the still is not much impacted.	[72]
Numerical analysis	Double slope solar still (DSSS)	CFD	SIMPLE	NA	Three dimensional	Yes. The difference in results for both models is less than 25%. The error of the results is 15.33% compared to the filed data.	Intensity and direction of solar radiation and temperature gradient	The rate of freshwater productivity rises as solar radiation increases in intensity, and vice versa.The freshwater productivity may be increased by 15% to 62% by installing a thermoelectric coolng system (TEC) over a portion of the glass, according to research.	[73]

6. Future Ways and Research Gapes

The state-of-the-art literature review highlights the following future research directions and recommendations to enhance CFD applications in studying the performance of solar still systems.

- The impact of the most common parameters that affect solar still productivity can be investigated and studied using CFD such as cover material, its angle, and its thickness, raw water type (lake, seawater), basin material and its absorptivity, and isolation materials between the system and the surrounding environment.
- Active solar still that is integrated with a solar system or internal heater can be simulated and investigated using the CFD tool.
- Solar still geometry optimization can be conducted by employing the CFD tool.
- Complicated solar still systems such as solar still with separate condensers or those with external heater systems can be investigated by utilizing the CFD tool.
- The impact of phase change materials (PCM) on solar still systems efficiency can be evaluated by using CFD.

7. Conclusions

The present study evaluated the use of CFD numerical simulations in assessing the performance of solar stills through systematic and bibliometric reviews coupled with content analysis. Among the 486 collected publications, 43 articles were further considered and analyzed. It was found that the CFD approach is a powerful tool that can be used to investigate and validate the performance of solar still systems under different climate conditions considering both evaporation and condensation processes. Moreover, CFD tools were found to be an applicable method to simulate different types of solar still such as single slope, double slope, pyramid, and tubular solar stills. Furthermore, detailed results, such as 2-D and 3-D renderings, can be produced from the CFD numerical modeling which can help to provide a better results visualization. Therefore, the CFD approach is recommended to be further used in assessing solar still systems and validating the experimental investigation for better improvement of their performances and efficiencies.

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