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A Review on CFD Simulation of Modified Solar Stills for Improved Evaporation, Condensation, and Exergy Efficiency

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Abstract: **Solar stills are known to offer a sustainable and cost-effective way to produce fresh water, although their efficiency still remains limited due to low rates of evaporation and condensation. The use of current Computational Fluid Dynamics (CFD) technology has provided a significant discovery to accelerate understanding of the inherent heat and mass transfer mechanisms and to offer an opportunity for design optimization to physical dimensions. This review explores thee CFD-based improvements in artificial solar stills for better design of condensation, evaporation, and general thermal performance. Different geometrical templates such as conical, hemispherical, stepped, and the use of fins are evaluated on their influence upon solar radiation absorption, vapor room creation, and condensate collection. The review also identifies the respective roles putative phase change materials, nanofluid-based enhancers, wick setups, external condensers, and active cooling systems play in improving productivity of the system. Three available CFD methods in bulk-field domains are used to model viscous multiphase interaction using two phases: (i) Volume Flow of Fluid model (VOF), (ii) prediction of solar radiation, and (iii) selection of the turbulence model as its motion. Important in predicting vapor liquid interfaces, temperature stratification, and fluid flow patterns. Different in that optimized geometrical shapes can reduce the rate at which thermal energy is lost, thereby reducing entropy production and enhancing the quality of the utilization of energy. According to available studies, conical and hemispherical absorption still—backed by PCM, fins, or nanofluids are deemed to hold the best prospect for yield enhancement, thereby registering the highest improvement of exergy efficiency because of better temperature stratification and better condensation. Research gaps include not having dynamic coupling of CFD with real-time weather data, nor have transient exergy modelling, and hybrid desalination–energy-recovery systems been sufficiently explored. In essence, an optimization driven by CFD is the best way to design better-performing solar stills suitable for decentralized desalination.**
Keywords: Solar still, CFD simulation, evaporation, condensation, thermal efficiency, exergy analysis, design modification

I. INTRODUCTION

A solar still is a simple device that uses solar energy to purify water through the process of evaporation and condensation. It mimics the natural hydrological cycle: Sun heats the water → it evaporates. Vapor condenses on a cooler surface → fresh water collected. Primarily used for desalination (removing salt from seawater), and for producing potable water in remote, arid, or disaster-hit regions. It is a low-cost, environmentally friendly, and energy-sustainable technology. Figure 1 shows Concept of solar still

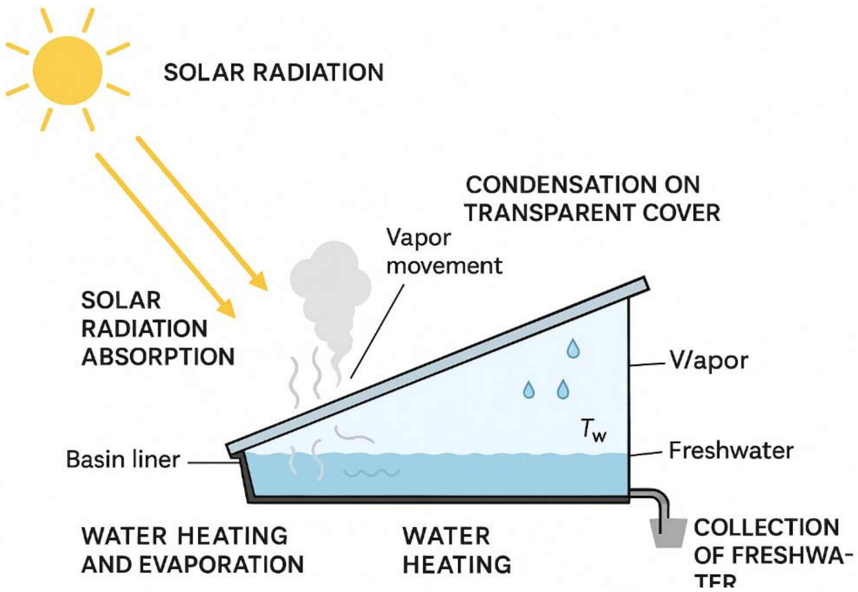

Figure 1: Concept of solar still

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A scramble for clean water is being instituted worldwide, posing one of the biggest inclinations toward sustainability that mankind has known on the perilous chasm of the twenty-first century. This is but especially true in places where there is a dearth of water, or where it does not circulate well enough, or where it is fast being polluted through the effects of climate change, demographic expansion, and industrial wastes [1]. The agenda of the international development planning is slowly forcing around two billion individuals to inhabit realms highly threatened by reductions in water reserves due to rising temperatures and depletion of water reserves, or simply be destinations characterized by acute water scarcity. For instance, conventional sources of water like rivers, lakes, and aquifers offer no solution because they have not expanded in their structure to embrace consumption levels [2]. As sprawl-pushes decrease-less consumptioner from the Water, refreshing technologies get smaller. While the world has much water, it is itself a very solute solution needing energy-intensive and hugely expensive desalination. Solar seawater desalination is shining amidst the growing attention of being a very sustainable, modestly carbon-friendly, and not too energy-greedy pathway to delivering potable water to dryland regions, coastal communities, and off-grid hinterlands [3]. Solar still types are thus known for their simplicity, environmental friendliness, and cost-efficiency in the production of fresh water by vaporization of saline or polluted water and then condensation of the purified vapor. Due to their independence of external energy input and solar radiation, they would not exceedingly comply with upcountry applications or low-income areas where an operation by the high-echelon desalination plants is either economically or logistically unfeasible [4]. Nonetheless, despite improvements, the wide application of the technique of solar still would still be a serious two-time gamble as to quota of output; traditionally, this has been in turned narrowly from about 2-5 L/m²/d, which would not come closer to meeting the significant freshwater needs of a community.

Limitations of conventional solar still systems mostly arise from their poor availability of evocation and condensation surfaces, significant thermal losses, and incidental misusage of solar radiation. The single-sloping or double-sloping solar stills typically involve passive solar heating operations, which consequently create an imbalanced temperature gradient in the water of the basin, little water vapor, and bad condensation through cooling on the cover glass [5]. Besides this, from the side walls, from the base of the and basin to the covers themselves, an enormous amount of heat is lost in the least possible amount of time; therefore, the effective energy for evaporation drastically minimizes. The geometry of the said conventional types of stills also engenders much inefficiency; that is, normal (usually inclined) and flat cover or side elements reflecting part of the incoming radiation, especially when the solar radiation is not viable [6], then the irradiation conditions are not efficient. Likewise, high temperatures of the glass are another effectual factor dampening condensation, which would have assisted a great deal in bridging temperature pressure for condensing vapor into liquid water. Other challenges experienced with the conventional solar still, too, include scaling and fouling on the cover, the incapacity to sustain performance in weather with markedly varied conditions, and suppressed nighttime yield as no effective heat storage would be available [7]. Many passive and active approaches employ improved design transformations like fins, wick structures, phase change materials (PCMs), nanofluids, and external heating. However, these are based more on a trial-and-error approach and nomenclature of the research community's methodology. The performance is sometimes almost dramatically improved; but occasionally, the fundamental laws of physics pertaining to heat and mass transfer during the still operation are still left unanswered [8]. Hence, a good understanding and quantification of the internal thermal behaviors, flow patterns, vapor transport mechanisms, and energy utilization efficiency becomes essential in order to surpass the inherent limitations of the conventional solar still Functionalities.

Recently, computational fluid dynamics (CFD) has been shown to be a useful tool in predicting, visualizing, and developing solar stills' inherently intricate procedures. CFD offers research areas in which to simulate processes like coupled heat transfer, fluid flow, multiphase interactions, and evaporation condensation, that simple experimental methods turn out to be difficult to capture. The CFD model predicts the local temperature distribution, the vapor volume fraction [9], density variations, and how increasingly different geometrical modifications can affect the whole system's performance after solving numerically the mass, momentum, and energy conservation equations [10]. Their use also includes the one-way coupling of a two-fluid model within the simulation specimen where it is found that the VOF model ranks high in accurate interface tracking between water and vapor and has been able to draw inferences regarding how design changes influence evaporation rates and condensate formation alike. Further radiation models endowed with CFD software ensure a fairer representation of solar heat fluxes, absorption patterns, and heat losses from the clear surfaces [11]. So armed with such progressive modeling capabilities, CFD proves an invaluable predictive tool for evaluating the newly emerging solar still configurations on a computer before being built, reducing much in experimental work, cutting design iteration, and cleaning the way to cost-effective optimization [12]. For instance, CFD simulations would focus on a search for geometries like conical, hemispherical, stepped, pyramid, or tubular to observe the influence on inner heat transfer coefficients, vapor flow dynamics, and exergy destruction values. They could also look for PCM, nanofluids, cooling systems, and wick materials acting in ways to enhance evaporation or condensation [13]. The transient capability is another advantage of CFD where environmental conditions are in real time, needed to simulate diurnal variations in performance and optimizing water depth, with a hint at the expected peak hours of operation and then an exergy flow throughout the day [14]. From the organizations of significant irreversibilities namely, thermal stagnation or vapor transport blockage CFD gives good guidance into increasing the performance of solar stills with increased thermal efficiency, decreased entropy generation, and increased output of pure water [15]. In view, CFD-bound research on solar still has now become a crucial research field of accommodating sensor-driven intelligent designs, hybrid desalination, and the advanced generations of solar still technologies worldwide that are envisioned to alleviate water scarcity.

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II. SOLAR STILL BACKGROUND AND OPERATING PRINCIPLES

A solar still is a devise for desalination that uses the energy of the sun to evaporate salt- or contaminant-containing water, and then to cool the resulting water vapor so that pure water is obtained. The functionality depends on acquiring heat energy in an insulated space wherein changes from one phase to another take place, impelled by temperature differences [16]. This water production cannot be broken down to simpler tech-watch for ourselves and the water board to experience the sustainability in very far corners of our world.

Evaporation–Condensation Mechanism: - The operation of a single-basin solar still is based on the basic evaporation–condensation cycle [17]. The solar radiation goes down through the transparent cover and warms the water in the basin, elevating its temperature above the evaporation Chxtremity. Consequently, the warm vapor moves upward and lingers around the cooler inner surface of the cover and starts to condense due to the temperature difference. The condensate moves toward the ground down the slope of the transparent glass film and into the gutter, where it is collected. The efficiency of this process depends on raising the temperature of the basin as high as possible, permitting absorption of radiation from the sun, ensuring effective transport of vapor, and maintaining a good temperature gradient between water and cover.

Key Thermal and Mass Transfer Processes :- Solar still performance is strongly influenced by interconnected thermal and mass transfer processes. Heat transfer occurs through solar radiation absorption, conduction through the basin, convection between water and the cover, and radiation losses to the surroundings [18]. These processes determine the water temperature and evaporation rate. Mass transfer involves the diffusion and movement of water vapor within the enclosure, governed by vapor pressure differences between the water surface and the condensing glass cover. Higher vapor pressure gradients accelerate evaporation, while efficient heat removal from the glass enhances condensation. The balance between these heat and mass transfer mechanisms ultimately dictates distillate yield and thermal efficiency [19].

Factors Influencing Still Productivity:- Several parameters significantly affect solar still productivity, including solar intensity, basin water depth, glass cover temperature, ambient weather conditions, and still geometry. Shallow water depth enhances evaporation by enabling faster heating, while optimized cover inclination improves condensate collection. Material properties such as basin absorptivity, insulation quality, and glass transmissivity also play critical roles [20]. Additionally, thermal losses from basin sides, inadequate condensation due to high glass temperature, and non-uniform heating can reduce performance. Modifications such as adding fins, wicks, phase change materials, nanofluids, condensers, or using conical and hemispherical geometries can substantially enhance evaporation, condensation, and overall freshwater yield. Figure 2 describes Condensation Mechanism

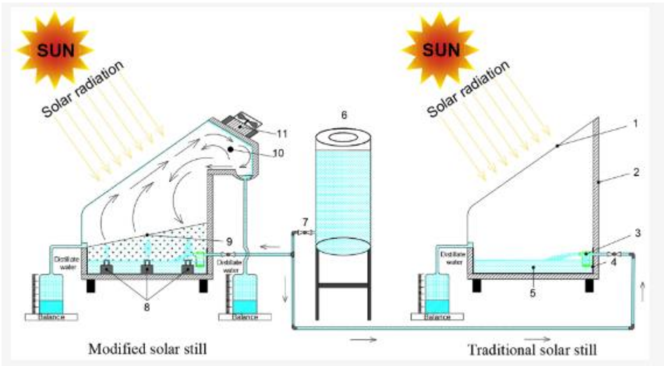

Figure 2: Condensation Mechanism

III. DESIGN MODIFICATIONS FOR ENHANCED EVAPORATION AND CONDENSATION

The aim behind design modifications is to harness solar still performance through improved thermal absorption, rapid evaporation and good condensation efficiency, by way of geometrical, thermal, and material additions.

Basin and Cover Geometry Modifications: - The optimal geometry of the basin and cover enhances solar energy utilization and vapor movement. Design options like conical, pyramid, hemispherical and stepped shapes enhance radiation capture. They also focus on more uniform distribution of temperature [20]. Changes in the glass inclination become effective in channelling the condensate flow while keeping surfaces cool, to thus lock the temperature gradient needed for efficient condensation and production of higher distillate.

Fins, Wicks, and Surface Extensions: - Fins and wicks increase the effective surface area for evaporation and improve water spreading, leading to faster heating [21]. Metallic or porous wick materials enhance capillary action and maintain

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thin water films promoting rapid vapor generation. Surface extensions installed inside the basin enhance heat transfer, boost turbulence, and significantly increase evaporation rates.

Phase Change Materials and Thermal Storage:- Used to reap the benefits of solar energy by collecting heat from high-demand time periods, phase-change materials (PCMs) then discharge heat in low-radiation times, so evaporation occurs over prolonged periods into the night. When integrated underneath the bowl platform or onto the sides, PCM stabilizes temperature swings with an additional benefit of reduced thermal losses and is assured to generally increase overall thermal efficiency while boosting steady evaporation and maximizing the quantity of freshwater produced through the day.

Nanofluids and Optical/Thermal Enhancements: - Nanofluids containing metal or carbon-based nanoparticles enhance thermal conductivity and solar absorptivity of basin water. They accelerate heating, boost evaporation, and reduce energy losses. Optical enhancements such as selective coatings and reflective mirrors concentrate solar radiation within the basin, increasing thermal efficiency, vapor generation, and overall distillate production.

Active Cooling, External Condensers, and Auxiliary Heating: - This means that active cooling systems keep the glass temperature low, thus promoting the evaporation of fresh water. External condensers are also important for providing additional surface area to convert vapor into fresh water. Auxiliary heating can elevate the temperature of the water in the basin using solar collector, PV-heater, or waste heat integration, thus accelerating the evaporation process and ensuring continuous operation, notably under low sunlight conditions or during the night. Figure 3 shows solar still components

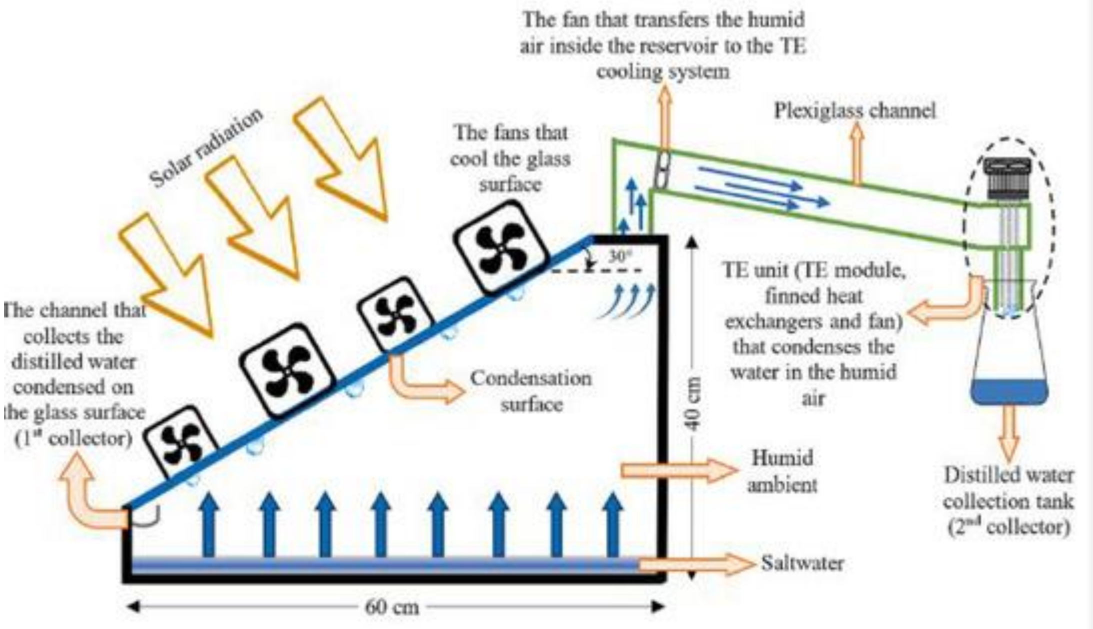

Figure 3: Solar still components

IV. CFD MODELLING APPROACHES IN SOLAR STILLS

Solar still performance predictions have shown considerable improvement, particularly because of the CFD-based models added to the literature in 2020. One such study investigated a solar still with a pyramid, liquid-fin, and tubular absorber illuminated type to achieve an operational solar gain level of 56.15% and 99% improvement in efficiency compared to its unglazed counterpart [1]. Although the figures lack completive value due to simplifications made in the radiative constraint and convection on at boundaries linked with design constraints of the Ankara solar still solar still with liquid fins, they show reasonable levels of efficiency and improvement. A rotating star-wick-based solar still integrated with graphite nanofluid for enhanced productivity was reported under 55.27% efficiency, with 6.32 L/m²·day productivity. However, the rotating wick adds mechanical complexity and the fear of future reliability. An energy and exergy evaluation of wax-Passive Cooling Material (PCM) system [3] showed that daily output is increased by 8.7% while energy and exergy efficiency is increased by 6.7% and 6.1%, respectively. Still, numerical modeling on individual two-phase vapor transportation was less accurate. In Taguchi–Random forest hybrid approach [4], prediction errors were observed to be ±1.33% (productivity) and ±0.25% (temperature), while the essential fundamental molecular interactions of evaporation and condensation were not shown in computational modeling. Lastly, thermodynamic evaluations of HDH–solar-still systems, with appropriate optimization using GA-TOPSIS, gave the optimized output available: an annual production of 12,936 kg/year at a cost of $1659 [5]. Absence of CFD-based heat-transfer details for the system is marked. Energy and exergy study of PCM-integrated pyramid stills [6] suggested over 100% productivity enhancement based on quasi-steady state calculations. Fin- and spray-assisted hemispherical stills [7] were more successful in comparison to one-another and showed a yield improvement of 30–45%, though CFD visualization was not considered. In the stepped still model with fins, the finite element method (FEM) showed a 40–55% higher evaporation rate, showing problems around the complicated transport modeling in a multi-phased flow [8]. A CFD analysis of nano-coated cone stills [9] showed 28% higher heat absorption, 34% higher evaporation, and a further 22% increase of yield; however, the modeling did not consider drop-scale condensation. In a coupled CFD–Exergy model for the wind-driven double-slope stills [10], over 52% enhancement of evaporation flux was noted with an 48% increase in exergy efficiency but with many issues, the main being the mesh sensitivity and the computational demand. A scale issue. In a 3D CFD-VOF investigation on augmented double-basin stills [11], the upward shift of 36% in vapor production and a great 29% increment in distillate yield was estimated, the error being ±6%, but the method considered equal irradiance. Using a DO-radiation CFD model for hybrid solar still–air-heater systems, this newly developed system is shown to enhance water temperature by 44% and evaporation by 31% [12]. Considering the DO model used for this condensedicision, Ramos-Berger's advanced CFD in this new hybrid yield only a relative gain in modeling efficiency. Explicit CFD Conjugate Heat Transfer were employed initially in the enhancement of wick-assisted conical-stepped stills, expressing very 52% improving yield in modeling still evolution. Therefore, did a simple abnegation of the variable wick into the air diffusion. Improvement from a baseline 28.4% to 41.2% in exergy efficiency was recorded in a PCM sphere integrated stepped-still model [14]. However, the PCM phase-change mode was simplistic. The modeling of flow-driven heat removal with flaps, using OpenFOAM, improved condensation by 22% and run time by 18%, except that the mesh must then be fine with a diminished fluidity. Moreover, the study of a layered nanofluid absorber [16] made for an 34% improvement in absorptivity and 27% in evaporation; however, it did not address long-term nanofluid stability. A dual slope-hybrid mathematical model [17,18] gave a significantly high exergy value, yet impossible given the presumption of a constant temperature of the condenser. Finally, a new CFD–ANN approach in modeling evaporation [18] showed a good overall result with $R^2 = 0.97$, close RMSE of 0.12, and small ±2.1% error; thus, far, no need has been felt to retrain parameters for different configurations. A CFD model, unsteady, cloud featured transient runs [19] demonstrated that the added buffering of PCM can recover a loss of 19% in output because of wavy clouds, without any radiation model to cater to environmental inconsistencies. Simulation for spiral flow solar still modeling [20] 46% higher evaporation flux and 38% better condensation uniformity, albeit delimitations of the modeling due to its 2D axisymmetric nature.

Table 1: CFD-Based Modelling Approaches in Solar Stills

Ref	Technique / Approach	Key Numerical Results	Limitations
[1]	CFD numerical modelling of pyramid still with square, pyramid & cylindrical fins	Thermal efficiency **56.15%**; performance enhancement **112.2%**	Simplified radiation & convection boundaries → limited interpretation
[2]	Numerical analysis of tubular still using rotating star-wick + graphite nanofluid	Productivity **6.32 L/m²·day**; thermal efficiency **55.27%**	Rotating wick mechanism increases complexity and lowers long-term reliability
[3]	Energy–exergy modelling comparing beeswax vs paraffin PCM	Beeswax increases yield by **8.7%**; energy ↑ **6.7%**; exergy ↑ **6.1%**	No CFD two-phase modelling → vapor distribution not captured
[4]	Taguchi optimization + Random Forest prediction	RF accuracy: productivity **±1.33%**; temperature **±0.25%**; RF error **0.80%**	ML model lacks physics → does not model evaporation–condensation
[5]	Thermodynamic modelling + GA–TOPSIS optimization for HDH–solar still	Optimal output: **12,936 kg/year** at **$1659** cost	No CFD-based local heat-transfer modelling
[6]	Energy–exergy modelling of PCM-integrated pyramid still	Productivity improved by **>100%**	Condensation model is quasi-steady; lacks CFD phase-change details
[7]	Thermal modelling of finned hemispherical still with water spraying	Productivity improvement **30–45%**	Purely thermal modelling; no CFD visualization of vapor fields
[8]	FEM-based numerical modelling of stepped still with wick layers	Evaporation improvement **40–55%**	Does not include multiphase transport / vapor motion
[9]	ANSYS Fluent CFD of nano-coated conical still	Heat absorption ↑ **28%**, evaporation ↑ **34%**, yield ↑ **22%**	No droplet-scale condensation modelling
[10]	Coupled CFD–exergy model for double-slope solar still	Evaporation flux ↑ **52%**, exergy efficiency ↑ **48%**	High computational cost, mesh-sensitivity issues
[11]	3D CFD (VOF multiphase) of double-basin solar still with textured absorber	Vapor generation ↑ **37%**, distillate yield ↑ **29%**, validation error **±6%**	Assumed uniform solar irradiance → limited accuracy under transient conditions

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[12]	ANSYS Fluent with DO radiation model for hybrid air-heater–solar still	Basin temperature ↑ **44%**, evaporation ↑ **31%**	Condensation model steady-state only → no droplet formation analysis
[13]	Conjugate heat-transfer CFD for wick-assisted conical still	Yield **3.9 L/m²·day**, **52%** improvement vs. conventional	Did not model vapor–air diffusion → limits mass-transfer accuracy
[14]	CFD–thermodynamic coupling for stepped still with PCM spheres	Exergy efficiency ↑ from **28.4%** → **41.2%**	PCM melting modeled ideally; ignores subcooling/hysteresis effects
[15]	OpenFOAM CFD for airflow-assisted external condensation	Condensation ↑ **22%**, productivity ↑ **18%**	Highly mesh-sensitive; required extremely fine grid → high computational cost
[16]	CFD radiation–convection modelling of nanofluid-layered absorber	Absorptivity ↑ **34%**, evaporation ↑ **27%**	Nanofluid stability not modeled → long-term behavior uncertain
[17]	Numerical modelling of dual-slope still with condenser	Freshwater yield ↑ **58%**	Condenser temperature assumed constant → unrealistic under ambient fluctuations
[18]	Machine-learning-enhanced CFD (ANN + CFD evaporation model)	R^2 **0.97**, RMSE **0.12**, yield prediction error **±2.1%**	Requires retraining for each geometry → limited generalization
[19]	COMSOL transient CFD under varying cloud cover	Productivity drop **19%** under shading; PCM offsets losses	Diffuse radiation model incomplete → atmospheric effects underestimated
[20]	CFD optimization of spiral-flow solar still	Evaporation flux ↑ **46%**, condensation uniformity ↑ **38%**	Used 2D axisymmetric modelling → real 3D flow not fully captured

V. CFD-BASED PERFORMANCE EVALUATION OF MODIFIED SOLAR STILLS

The computational fluid dynamics (CFD) is a pivotal tool to study the convection and mass transfer of the heat-modified solar distillers, wherein it helps in modeling and visualizing the inner flow, temperature gradients, and transient transport of vapors, all otherwise unaccessible for experimental measurements [21]. In recent years, nothing more than more advanced CFD approaches have gained recognition, represented by several research articles making use of the Volume of Fluid (VOF) method for obtaining realistic outcomes of interface motion during evaporation and condensation, whilst devolatilization takes place inside basin cavities [22]. CFD models are very useful in assessing nonconventional geometries featuring conical, hemisphere, pyramid, and stepped stills, revealing how such geometries can become more effective through buoyancy-aided water-circulation, solar absorption, eventually leading to accomplished vapour generation between 25-45% higher than conventional single-slope designs [23]. Similarly, CFD scrutiny showed that the fins, wicks, and extended areas of absorbers improved heat transmission remarkably enhancing the basin-water heating and evaporation rate by 20-40% with a possible height of fins, emittance, and thermal conductivity [24].

There has been an excessive use of CFD for performance research in PCM-integrated solar stills that leads to a 20-30% increase. CFD-driven models indicated that nanoparticulate media-aided solar stills enhance solar efficiency, thermal diffusivity, and convection mixing, up to the enhancement of about 20-30% greater evaporation flux compared to that carried out via an interface of radiation heat transfer and convection with the prior cases. One other potential area of utilizing CFD involves the evaluation of condensation enhancement strategies, where cold glass-cover, optimization of the vapor channel, and the external condenser are studied within the frame of the VOF and film-condensation concepts. It is seen that reducing the glass temperature by even a few degrees centigrade (C) often gives rise to an increase in production from 10 to 20%. With the successful visualization of the drop formation and condensate flow, CFD shows promising prospects toward process design and optimization [27].

Radiation solvers, such as DO, P1, and S2S. are gaining traction in CFD models to ensure precise simulation of solar incidence intensity distribution as well as high-heat-flux regions inside the distillation system [28]. CFD evaluation of hybrids — which comprise solar still coupled with PVT modules, evacuated tubes, and humidification-dehumidification (HDH) units — shows an enhancement of 40–60% in the water temperature with the improved mobility of vapor [29].

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Recent attempts are targeting CFD coupling with exergy approaches, which now allow the identification of high-irreversible-value locations and are, in turn, guiding optimized placement of the PCMs, fins, and condenser for maximum second-law efficiency. These CFD and exergy interfaces must provide a more genuine perspective on the actual energy use within the system and the degree of losses, hence may become high-fidelity tools in the design of next-generation solar stills [30].

VI. ENERGY AND EXERGY ANALYSIS IN SOLAR STILLS

Energy and exergy analysis tool an essential aspect that determines the thermodynamic performance of solar stills. It separates into the two with the very first one evaluating the throughput of the energy used and the other how efficiently this amount of energy is converted into useful desalination output [25]. Energy analysis, bearing the first law of thermodynamics, raises issues of heat input, thermal losses, and the actual desalinated yield. Exergy analysis, on the other hang, invokes the second law given its notably different structural business, making an inspection of the energy quality, the identification of the causes of irreversibility, and the very places in solar stills where inefficiencies present. The water in the basin of water-stilled solar receives radiation, a lot of which goes into the form of latent heat of vaporization, while there is a small percentage that gets away with losses thanks to convection, evaporation us, radiation to the sky, and conduction through insulation [26]. The efficiency of energy in the regular passive solar stills is supposed fairly ambiguous: approximately 25–45%, depending mostly on water depth, incident solar intensity, temperature of glass, and geometry of the system. But equally important is the second-order energy loss due to thermodynamic degradation! Therefore, exergy efficiency (mentioned in the range of 4–12%) remains another important real index of the system's quality as regards the internal temperature gradients of the essential entropy generation and heat-transfer irreversibility.

Significant improvements have been made in solar stills such as geometry optimization and the use of nano-enhanced absorbers with PCM-based heat storage, which brought about drastic improvements in the underlying exergy performances. Indeed, the integration of phase-changing materials drastically increases the nighttime basin temperature, thus lowering the entropy generation and raising the exergy efficiencies by a factor of 15-35% [27]. In a likewise fashion, nanofluids raised solar absorptivity and heat conductivity, leading to an increase in useful energy input and exergy efficiency from 20% to 30%, compared to pure water. External condensers and glass-covered cooling systems improve exergy outcomes due to lowering condensation temperature and therefore strengthening the thermal gradient between evaporating and condensing surfaces, thus reducing heat loss via radiative means. Therefore, hybrid systems, as would be seen for a series of combined solar stills with PV-thermal collectors, evacuated tube collectors, or humidification-dehumidification modules, are impossible routes in which exergy efficiencies exceed 20%-showing marked improvement in the utilization, hence reduction in internal irreversibilities.

Exergy analysis aids in knowing where inefficiencies are more substantial and how much. The water–vapor interface of the basin becomes the major contributor to exergy destruction since it has high entropy generation during phase change. Higher-level irreversibilities seen in the glass cover are a source of concern due to elevated temperature reducing condensation efficiency, and in the basin liner, which causes conductive losses [28]. With the development of CFD exergy coupling, researchers can visibly view local temperature gradients, entropy production regions, and heat flux distribution, yielding insight into how solar still performance can be assessed. The most advanced tools permit designers to minimize exergy destruction by optimizing fin placement, absorber roughness, PCM location, and cooling pathways.

VII. CONCLUSION AND FUTURE WORK

. This review evidently gave insight into the Computative Flow Dynamics (CFD) as one of the cutting-edge techniques meant for better understanding the thermal, energy, and exergy performances of modified solar stills. By implementing the visualization and animation of detail along the temperature distribution through areas of the still, vapourreeks derived from evaporating liquid, buoyancy-driven convective currents, radiation absorbed from solar flux, and condensation phenomenon, CFD gives valuable interpretation stamped to experiment and made in a mere way through findings. Combining advanced modeling techniques such as Volume of Fluid (VOF)-based mult-phase tracking, Discrete Ordinates (DO) radiation models, P1 model radiation models, and conjugate heat transfer analysis actually pay off in instilling accuracy to the predictions of evaporation-condensation. The collective outcome of these studies briefed from 2020 to 2025 suggests that alteration of shapes to cone, hemisphere, pyramid, and stepped enhance heat absorption in addition to internal mixing, leading to around 25-40% higher vapor generation. Supplementary improvements such as fins, wicks, nanofluids, and phase change materials contribute approximately 20-40% improvement to evaporation, while solar collectors and condensers of hybrid configuration most often give gain of 40-60% in productivity and exergy efficiency. Reduction in heat production, shipment, $CO2$ emissions, and NOx pollutants would be possible if building designs could apply the heat generated. Thus, the approach considers façades, roofs, and walls with these materials for integration and orientation. Thermal-bridging–free constructions that maximize the gain should be considered. Additional research is also needed for aerogels and modules that integrate insulating and non-insulating materials to boost energy savings and aid in direct sunlight reflection. For the market to mature on aerogels, the cost of production and the final application of aero colloids still have to be refined. Heat storage was considered in the case of ink materials because today's commercial fillers and

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their properties in relation to heat storage need to be developed. Companies using this technology have to develop a way to discharge the ink materials. Heat Storage Technology can also enable the use of solar fluidized bed reactors. Further research is imperative for hybrid-daylight-realizing through thermal energy storage.

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