A Comprehensive Review of Performance Enhancement Techniques in Double-Slope Solar Stills

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Abstract:

Double-slope solar stills receive much attention in sustainable freshwater production for their easy operation as well as their low operational costs and efficient energy utilization. However, their limited production capacities motivated further development in performance enhancement. Within this domain, optimization of geometrical parameters holds a crucial position as it enhances the solar radiation absorbed, heat-transfer devices, and condensation removal. This paper presents in detail the various modifications made for the best design parameters in terms of tilting angle, basin depth, configuration of glass cover, aspect ratio, and spacing between components. These parameters are tested against operating conditions and auxiliary enhancements (e.g., reflectors, phase-change materials, wicking materials) for improving the distillate yield through a theoretical analysis. We also discuss possible modeling approaches, experimental findings, comparative performance metrics highlighting the most suitable design configuration. The manuscript eventually provides an updated outlook on existing research and paves the way to maximize freshwater generation and maintain economic sustainability and feasibility for real applications.

***Keywords**:Double-slope solar still, Geometrical parameter optimization, Solar desalination, Productivity enhancement, Heat and mass transfer, Sustainable water purification*.

I.INTRODUCTION

The increasing scarcity of freshwater resources due to population expansion, industrialization, and climate change has created a strong drive to look for sustainable and energy-efficient desalination technologies. Solar desalination technology has emerged as a promising approach because of rather low environmental impacts and suitability for use in decentralized forms, especially in remote and arid areas [1]. Among these various configurations of solar desalination systems, double-slope solar stills have been gaining a lot of interest primarily because of easy fabrication, utilization of both direct and diffuse sunlight, and enhanced collection of condensates from two sloped glass covers. However, the performance of double-slope stills is severely limited by their low fresh-water yields. Consequently, the research has been highly active in the attempts at various performance-enhancement techniques for evaporation, condensation, and overall thermal efficiency. Technological endeavors such as thermal energy storage, nanofluids, wick materials, reflectors, external condensers, and hybrid photovoltaic integration have shown quite improved performances [2]. However, while demonstrating great improvement, almost all of these successful improvements make the configuration excessively complex or the economics heavily burdensome. On the other hand, optimization of geometrical factors is a money-saving, structurally uncomplicated, and yet truly effective way of improving the performance without changing the fundamental solar still working mechanism [3]. The geometry optimization of a solar still is almost indispensable, as the system performance is mostly influenced by the geometrical characteristics like the inclination of the glass cover, depths of the container, aspect ratio, internal spacing, and several structural configurations that should determine solar energy absorption and heat and mass transfer processes and finally the flow characteristics of condensation [4]. Optimizing them will substantially improve the fresh-water yield from the system and, at the same time, maintain simplicity of the system to enable a higher level of scalability. Therefore, a comprehensive review on recent advancements in geometrical design optimization is required to define the optimal design guidelines and to open up further research directions [5]. The review here gives a critical analysis of performance enhancement methods for a double-slope solar still with especial focus on the optimization of geometrical parameters, thereby imparting guidelines and directions for contemporary knowledge regarding development of efficient, sustainable, and economically viable solar desalination techniques. Figure 1 represents double slope solar still

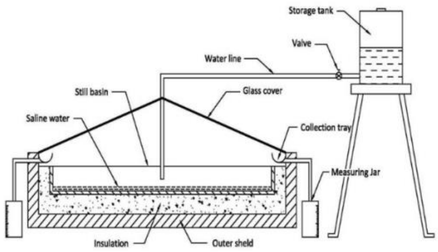

Figure 2: double slope solar still [31]

Global Water Scarcity and the Need for Sustainable Desalination

The gap has intensified the global scarcity of water, particularly in the semiarid and arid regions, between growing freshwater demand and the available natural resources. Conventional desalination technologies, while effective, are heavy in energy and capital with environmental threats bleak from the perspective of fossil fuel. Solar-driven desalination systems are currently replacing the traditional systems as sustainable alternatives [6]. This technology is characterized by minimal energy costs, minimal environmental disruption, and most importantly, accords to field trials where they are placed in an off-grid setup [7].

Overview of Double-Slope Solar Stills

Among solar desalination devices, solar stills are the simplest, in which the natural evaporation-condensation cycle is used to produce fresh water. Compared to single-slope devices, double-slope solar stills use the entire solar radiation resource-including direct and diffusion-radiation collections throughout the day. Double-slope solar stills have symmetrical glass covers over the basin that collect condensation on both sides, making them particularly ideal for regions in which the sun's elevation keeps changing throughout the year [8]. As much as these methods could serve the purpose, the fresh water productivity for conventional double-slope solar stills remains quite low and therefore calls for continued efforts at enhancement.

Development of Performance Enhancement Techniques in Double-Slope Solar Stills

Geometrical modification has always been a simple, low-cost intervention; it does not interfere with the basic operating principle behind the solar still. Shamelessly, throughout the so-called refurbishment effect categories, geomod is the only free area to roam with unique architecture. Widely used geometrical parameters analyze the absorption of solar radiation, internal heat, and mass transfer, and water-condensation capabilities within the double-slope solar stills [9]. Parameters like the inclination of glass covering, basin depth, aspect ratio, gaps between or spacing behind arrays, and structural configurations further impact on rates of evaporation and condensate yield. Optimization of these parameters has well-established bounds and ramifications in improving the thermal behavior, further upholding the simplest and most cost-effective systems. Therefore, the focus of the current research is on the geometrical parameter to raise productivity in the double-slope solar still [10].

II. FUNDAMENTALS OF DOUBLE-SLOPE SOLAR STILLS

Double-sloped solar stills, simple and passive desalination systems, operate on the principle of natural evaporation and condensation to generate drinkable water from contaminated or saline water. The basic arrangement comprises a shallow basin holding saline water, a blackened surface to enhance solar heat absorption, and two inclined glass covers that symmetrically protect the basin from each side [11]. This dual-slope setup literally gets the advantage of direct solar radiation and that of diffuse (indirect) solar radiation during the day, improving energy efficiency of the system compared to single-tilt designs. Solar radiation passes through the glass covers and is absorbed by the basin liner, increasing the temperature of the basin water and leading to evaporation [12].Figure 2: The layout of experimental test-rig of TDSSD A and DSSD-WPB&DPSN B. [32] and Figure 3: Photographic view of the test-rig of TDSSD A and DSSD-WPB&DPSN B [32].

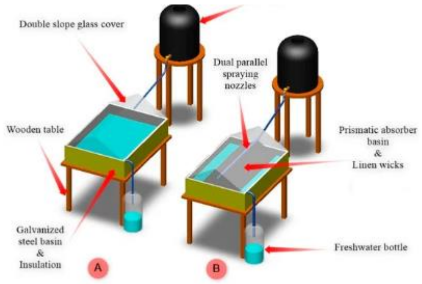

Figure 2:The layout of experimental test-rig of TDSSD A and DSSD-WPB&DPSN B. [32]

Figure 3: Photographic view of the test-rig of TDSSD A and DSSD-WPB&DPSN B [32]

As the temperature of the water rises, water vapor begins to build up in the still and condense on the slanted glass covers which, being cooler compared to water in the basin, act as condensation sites for the vapor. The temperature difference between the vapor and the glass cover encourages condensation as water droplets are formed on the inside surface of the glass [13]. Gravity then causes them to slide down the inclined glass covers, where they are ready for collection in side catchments into a storage tank. The double-slope configuration encourages the most well-distributed production efficiency throughout the day with more condenser per side [14].

Heat transfer within a double-slope solar still occurs through a combination of respective radiative, convective, and evaporation-condensation mechanisms. While solar radiation contributes the energy input, convective and evaporative heat transfer processes contribute towards the output of freshwater from the heated water surface to that of the glass cover. Important parameters such as locality of cooling, basin contingencies, glass cover inclination, ambient temperature, wind state, and solar flux exert a significant effect on the solar still's potential performance [15]. Based on the simplicity of design, low need for maintenance, and ability to operate without auxiliary power input, double-trough solar stills critically consider and become a serious water-purification answer. Hence, high heat losses and slow evaporation will actually suggest design optimization studies in order to increase efficiency, thereby forming fertile grounds for further research into geometry and operations' advancements [14]-[15].

III. KEY GEOMETRICAL PARAMETERS INFLUENCING PERFORMANCE

The geometric configuration dictates the solar radiation-absorbing ability, the internal mass and heat transfer, and the condensation efficiency of a double-slope solar still. Among these, the inclination angle of the glass cover is of major concern, because it dictates the amount of solar radiation reaching the bottom of the still and the speed at which the condensate flows to the sides [16]. Optimized such an inclination is able to both collect additional solar energy and facilitate the removal of condensate so droplets steer clear of falling back into the basin. Basin geometry that determines the basin depth, width, and water depth ratio is the key factor in controlling the thermal behavior of any system. With shallow water depth, the water temperature increases rapidly, leading to higher evaporation rates; however, excessive water depth increases thermal inertia, reducing productivity. Basin dimensions affect the exposed evaporation area and water vapor distribution within the still, thus affecting overall water gain [17].

The water preservation height and good depth relative to the width of the basin are also critical in the production of water. Proper inter-space spacing promotes the effective generation of water vapor and its condensation, while too much space will lead to heat losses thus reducing condensation rates [16]-[17]-[18]. Plus, the height and section of the distillation plant affect innards' immediate air current systems and temperature gradients, which directly affect the evaporating and condensing activities.

IV. EFFECT OF GLASS COVER INCLINATION AND ORIENTATION

Glass sloping angles and azimuthal orientations are major geometrical factors that influence double-sloping solar stills. The glass cover slope is responsible for the entry of insolation onto the basin, resulting in the rate of condensation and collection efficiency of the condensate [19]. Glass orientation relative to the solar path also helps in energy capture. Proper orientation in a double-slope configuration balances solar radiation between the east and west within the day. This symmetry helps maintain temperature somewhat evenly inside the stell and continues evaporation through the daylight hours. The correct inclination for the season is also key; the best angle will depend upon the latitude [20]. In order to maximize performance, appropriate designs must be strictly fashioned for different sites or latitudes. Glass inclination has an influence on the convective and radiative transfer of heat from the water layer to the glass cover. Properly inclined and oriented, covers will help maintain a desirable temperature gradient which, ultimately, accentuates condensation rate for vapor. It also has the added advantageof reducing shading, minimizing reflection losses, and enhancing overall thermal efficiency. Therefore, the correct choice of glass cover inclinations and orientations is greatly relevant to a higher freshwater yield, making it a top priority in geometrical optimization of double-slope solar stills [21].

Table 1: Performance Enhancement Techniques in Double-Slope Solar Stills

Ref.	Enhancement Technique	Methodology	Key Findings	Limitations
[1]	Cylindrical fins in basin	Experimental & numerical	Increased heat transfer area significantly improved daily distillate yield	Added structural complexity and material cost
[2]	Multiple advanced enhancement techniques	Comparative experimental analysis	Hybrid techniques showed superior productivity improvement	Difficult to isolate individual parameter effects
[3]	Optimization of heat addition methods	Experimental evaluation	Controlled heat input enhanced evaporation and yield	External heat source increases energy demand
[4]	Vacuum-assisted double-slope still	Experimental study	Lower boiling point led to higher freshwater productivity	Vacuum sealing and maintenance challenges
[5]	Water cooling of walls	Experimental investigation	Enhanced condensation rate improved distillate collection	Additional cooling mechanism required
[6]	Nanoparticles in basin water	Experimental analysis	Improved thermal conductivity increased evaporation rate	Nanoparticle stability and cost issues
[7]	Novel geometric design	Energy and water quality analysis	Improved productivity with acceptable water quality	Design scalability not fully addressed
[8]	Nano-enhanced PCM with wick material	Experimental study	Sustained nighttime productivity and higher efficiency	PCM cost and long-term reliability concerns
[9]	Wick materials with energy storage	Comparative experimental study	Capillary action significantly boosted evaporation	Wick degradation over long-term use
[10]	Metal–organic framework integration	Experimental investigation	Synergistic evaporation enhancement achieved	High material cost and availability
[11]	Process parameter optimization (Taguchi)	Statistical optimization	Identified optimal operating parameters for maximum yield	Limited to selected control factors
[12]	Stepped basin geometry	Experimental approach	Increased evaporation area enhanced productivity	Fabrication complexity
[13]	Optimized single-slope still (comparison)	Experimental & numerical	Demonstrated importance of geometry optimization	Single-slope focus limits direct applicability
[14]	Thermal management with energy storage	Experimental study	Stable performance under fluctuating solar input	Increased system weight
[15]	Glauber salt & graphene oxide PCM	Experimental analysis	Improved thermal response and yield	PCM leakage and cost
[16]	PV-integrated double-slope still	Experimental study	Combined water and power generation improved efficiency	Higher capital investment
[17]	Thermal energy storage with capillary effect	Experimental investigation	Significant enhancement in evaporation efficiency	Design complexity
[18]	Bio-mediated ZnO nanofluids	Experimental study	Eco-friendly nanofluids enhanced solar absorption	Nanofluid preparation consistency
[19]	Functional threshold optimization	Experimental analysis	Identified critical operating limits for productivity	Climate-specific outcomes
[20]	Natural fibers with nano-PCM	Experimental investigation	Sustainable materials improved yield and efficiency	Long-term durability of fibers

V. SPACING AND CONFIGURATION OF INTERNAL COMPONENTS

Spacing of the components within the double-slope still, even the whole arrangement, dominates the heat and mass transfer, thus affecting the production of freshwater. Basically, the vertical distance between the glass cover and the water surface of the basin will determine how far the vapors travel and condenses to bring in the condensate. The optimal spacing will assist in achieving a proper flow of the vapors and sustaining a sufficient temperature gradient between the surface of the evaporating water and the condensing cover for the glass [22]. More spacing will only raise heat loss and reduce the amount of water returning to the condenser, while less spacing will work against the flow of vapors and water. The arrangement and geometry of the interior elements determine how effective the system becomes [23]. The standard configuration leads to an increased heat transfer area, encourages turbulence in the basin water, and enriches evaporation rates. A concerted approach means that the temperature is evenly distributed within the still and any thermal dead areas [24]. Again, the set up and positioning of internal elements will also serve the purpose of determining the flow paths of exhaled moisture and its trajectory too. Carefully designed configurations should channel the condensed water right into the collecting channels, thus reducing the re-evaporation effects. Better internal spacing and configuration optimization will allow for effective evaporation and condensation enhancement, heat pump performance improvement, and a higher yield of freshwater, without burdening the system through added complexity or cost [24]-[25].

VI. INTEGRATION OF AUXILIARY ENHANCEMENTS WITH GEOMETRICAL OPTIMIZATION

Double slope solar stills have been subjected to thorough experimental investigation, as they are being considered as a highly effective passive desalination technology, which is due to their capability to use solar energy on both sides of the glass cover. With emphasis on enhancing freshwater productivity through variations in the internal heat transfer mechanisms and the structure configuration, the research is reported. There has now been an experimental and numerical verification of significant productivity improvements in heat transfer area as well as in turbulence within the SSWB by the introduction of cylindrical fins inside the basin [1]. To fortify performance, advanced enhancement techniques have been compared, of which, by the combined influence of thermal augmentation, material integration, and internal modifications enhanced concurrently. The results from those studies show that hybrid improvement approaches remain superior to single-parameter improvements in daily yield and efficiency [2]. Additionally, optimization of heat addition techniques has been shown to significantly enhance the evaporation condensation dynamics, clearly working well under different climatic settings, enhanced by controlled heating strategies [3]. In the domain of membrane distillation configurations, vacuum configurations have appeared also as potential solutions in which the boiling point of the saline water is lowered due to the reduced internal pressure producing the greatest fresh water. As reported by some experimental laboratory studies on the vacuum double tilt solar stills, significant enhancement in productivity relative to the conventional designs has been stated, though complexities of the system became an issue for their success, including sealing [12]. Furthermore, studies were undertaken to enhance the efficiency of condensation through cooling techniques in the wall, which concluded that the controlled cooling of the sidewalls enhances vapor condensation and improves overall distillate collection [13]. Nanotechnology-derived improvements have come into significant focus. In particular, nanoparticles dispersed in the feed basin were found to enhance solar absorption and thermal conductivity, thereby accelerating evaporation rates in single-basin double-slope solar stills [6]. In the wake of this, new geometric configurations are being scrutinized for the evaluation of energy efficiency and water quality to reveal that suitable structure design is a key variable for simulating higher distillation productiveness and higher distillate purity [7]. Off-grid solar stills have been investigated by many researchers (in general) who also enthusiastically pursue the integration of energy storage, nanoenhanced-phase-change-materials. Their energy storage properties help to prolong productivity into hours stretching beyond those of daylight. It was noticed that eutectic PCMs with capillary pump substantially increased operation time for condensed water under more or less optimal external conditions and improved the thermal efficiency [8]. Similar studies on different wick structures and materials for energy storage have all confirmed the same enhanced water yield caused by capillary-driven evaporation. [9] Further developments include the incorporation of new materials like MOFs (metal-organic frameworks) that can enhance evaporation efficiency through synergistic heat and mass transfer mechanisms. In fact, these materials could outperform under similar operating conditions, suggesting great promise for the next generation of solar distillers [10]. Various optimization techniques, using Taguchi parameter analysis, have been applied on passive double-slope solar stills to determine the combination of water depth, tilt angle, and insulation that yields performance enhancement as validated by statistics [11]. Stepped and tubular configurations have been tested experimentally to increase heat absorption and evaporation area, moving beyond traditional basin designs. These alterations in geometry have been shown to be really powerful in soaring production of freshwater, but with complexity of fabrication, it might be hard to achieve scalability [12]. In fact this design is particularly appreciated in desert environments once compared to your single slope technology [13]. Some double-slope solar stills portable and energy storage integration have been investigated in order to target freshwater needs in remote areas. Thermal management strategies with latent heat storage have shown steady operation and overall increased yield over traditional covers under changing solar conditions [14]. Further enhancement on large-scale outgrowths and long-term performance stability through the utilization of highly advanced PCM composite with Glauber salt and graphene oxide ha d saved energy, too [15]. To combine more functions, one can integrate solar-powered photovoltaic panels into wastewater treatment with double-pitch solar stills. Within these hybrids the hybrid systems are noted for a higher energy viability and more beneficial energy output though again with the cost being a major concern (16). By using suitable thermal storage media in capillarity mode, the efficiency and sustainability indices have been shown to grow substantially [17]. The experimentation demonstrated that the nanofluids were of a large influence: the photo catalysis rates and evaporation rates were increased by combining them with double-slope solar stills [18]. Various transformations involving the functionally operational and geometric adjustments are also being put under research to comment on critical parameters establishing productivity-boosts [19].

Table 2: Performance Enhancement Techniques in Solar Stills

Ref.	Enhancement Technique	Methodology	Key Findings	Limitations
[21]	Trigeneration double-slope still with PV and heater	Experimental & 4E assessment	Improved freshwater yield, power generation, and environmental performance	High system complexity and capital cost
[22]	External condenser with internal heating	Experimental investigation	Enhanced condensation rate significantly increased productivity	Additional energy input required
[23]	External reflector integration	Thermodynamic and experimental analysis	Improved solar radiation capture and water production	Performance depends on solar tracking and orientation
[24]	Polystyrene insulation with nanofluids	Experimental and economic analysis	Reduced heat losses and improved productivity and cost efficiency	Long-term insulation durability concerns
[25]	Channel shape variation	Experimental & numerical simulation	Optimized channels enhanced evaporation and condensation	Manufacturing complexity
[26]	Splitter plate and hollow circular fins	Experimental study	Increased turbulence and heat transfer improved yield	Added internal obstruction may complicate maintenance
[27]	Climatic performance assessment	Experimental evaluation	Demonstrated adaptability under coastal climate conditions	Region-specific results
[28]	Nanofluid-infused shallow collectors	Experimental analysis	Improved thermal absorption enhanced still efficiency	Nanofluid stability and cost
[29]	Climate-adapted phase change material	Experimental performance assessment	Improved thermal storage matched local climate conditions	PCM degradation over long-term use
[30]	Optimized water depth with thermoelectric cooling	Experimental and 4E analysis	Enhanced condensation efficiency and overall performance	Increased power consumption

VII. MODELING AND SIMULATION APPROACHES FOR GEOMETRICAL DESIGN

Modeling and simulation are sure of great assistance in optimizing the geometrical design of double slope solar stills by predicting heat and mass transfer behavior under varying conditions. Analytical models, numerical methods, and CFD simulations are popular tools to investigate the impact of basin depth, cover slope, and spacing for accurate performance prediction and optimal design justification.

Natural fibers when combined with nano-PCM composites have recently made some new developments as enhancement materials that sustain double marginal solutions in thermal energy it stores and capillary water-absorbing. These dual-profit processes have increased the interim standard cost without making the alteration in environment less in any way [20]. Trigeneration systems that are much more complicated in configuration, having the combination of photo-voltaic panels and further heaters, are analyzed in thermo-economic and environmental terms, resulting in attractive system performance and higher system complexity [21]. With the help of external condensers and an internal heating source, the physical performance is enhanced even more since condensation rates increase and vapor losses lessen [22]. Reflective-indoor double-slope solar distillers offer even greater potential for radiation capture, with higher water production being possible with proper thermodynamic consideration [23]. Modified double-slope solar stills improve thermal insulation and economic utilities by means of the lightweight material polystyrene foam coupled with nanofluids [24]. Experimental and CFD studies showed the fluid dynamics to be improved thereby mostly controlling the process of evaporation and condensation due to optimized channel design modifications in the still structure. Internal innovations like insertion of splitter plates and hollow circular fins were successfully designed to enhance turbulence and heat transfer respectively and in turn showed more measurable productivity returns [26]. The comparative climatic performance evaluation observed between different geographical locations serves to underscore the double-sloped solar still's adaptability under different environmental regimes [27]. Although most research emphasize slope design such as double slope, comparative information from single slope systems paired with Nano fluid-based shallow collectors gives substantial insight into the heat transfer augmentation mechanisms. Adapted phase change materials, developed to meet the requirements of local environmental conditions show the major importance of region related optimization strategies. Finally, advanced thermodynamic, economic, environmental, and energy (4E) analyses have shown the importance of a proper setup with optimized parameters contributing to the performance of a solar still [28].

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