Flow Simulation and Thermal Assessment of Salinity Gradient Solar Ponds: A Comprehensive Review

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Abstract:

Salinity Gradient Solar Ponds (SGSPs) are considered a promising solar thermal technology, which is able to collect and store solar energy through stable salinity-stratifying sea boundary-layers. Phase transition and long-term reliability issues are intrinsically linked to SGSP technologies, and these depend on the complex interaction between fluid flow, heat transfer, and mass diffusion phenomena. The present review therefore deals with a detailed evaluation of flow simulating and transport processes in SGSP, with a great focus on numerical modeling of convective suppression, stratification stability, and efficiency in terms of thermal energy storage. The primary and complex mathematical formulations that respect Navier–Stokes, energy, and species transport inequalities are discussed with the aid of cookery books on modeling of natural convection. Also critically, various methods of computation (finite difference, finite volume, and finite element schemes) are considered wherein Computational Fluid Dynamics (CFD) is presented as a possible way to predict field variables varying among temperature, velocity, and salinity in view of the different environmental and operational conditions. Experimental, numerical, and hybrid methods are systemically screened and exploited astray to ascertain the vitality of various zoometrics in dependence on pond geometry, boundary conditions, climatic factors, and multiphysical effects on double-diffusive convection: Soret and Dufour phenomena. Emerging areas that are highlighted, including integration with phase change materials and other advancement brought about through intelligent monitoring systems, as well as computer-based simulation frameworks that cater to these highly advanced technologies. The literature review concludes that further research is needed on major research gaps and challenges, covering such aspects as longitudinal stratification destabilization, model verification, and computational ease. The review concludes in the further prospects posed as future research directions to greatly uplift the conceptualization on SGSP design, analysis for performance verification, and scaling-up for renewable energy applications.

Keywords: *Salinity gradient solar pond, flow simulation, heat and mass transfer, double-diffusive convection, thermal energy storage, numerical modeling, CFD .*

I. INTRODUCTION

The global demand for sustainable and low-carbon energy solutions and increased global warming have triggered tons of research into solar thermal technology, simple, reliable, and cost-effective designs. Salt gradient solar ponds (SGSPs) are unique among categories, involving not only the collection of solar energy but the storage of this collected thermal energy in a single water body. SGSPs differ from conventional solar collectors as they do not require separate storages [1]. Density stratification is induced by salinity to suppress natural convection and ensure elongated heat retention at low construction and maintenance costs [2].

An Salt Gradient Solar Pond (SGSP) is usually stratified in the following way: typically the upper convective zone (UCZ) would be containing low salinity water and the normal ambient temperature; the non-convective zone (NCZ) that would transition with depth into a high salinity water shell; and finally, the lower convective zone presents with higher-salt water which is regarded as a primary heat storage region. Solar radiation penetrates through the upper layers and is mainly absorbed in the lower convective zone [3]. The gradual salinity concentration with depth would provide a stable density gradient that prevents any buoyancy-driven convection movements, thus, maintaining the hot and heavy lower stratification water in situ. The temperature in the LCZ may be brought up to 70-90°C, or even higher, depending on climatic conditions and design of the pond. SGSPs have been in the interest of those focusing on different applications including power generation, industrial process heat, desalination, space heating, and agricultural drying, especially in a region with plenty of land, the right amount of sunshine, and brackish water [4]. However, despite the relative straightforwardness of SGSP, their long-term performance and reliability depend on intricate fluid flow, heat transfer, and mass diffusion processes requiring more intensive scientific scrutiny.
The performance of the SGSP critically relies on how the interaction between flow dynamics, thermal transport, and salt diffusion evolves within the pond. Though the NCZ design aims at stagnation of the fluid, the stall was far from being perfect. But all these subtle modes of flows- the mechanisms of double-diffusive convection, shear-induced mixing, internal circulation, boundary-layer flows, and stratification destabilization- come into effect [5].

Heat transfer in the SGSPs is achieved through the solar radiation absorption, with conduction, limited convection, as well as loss at the surface due to evaporation, radiation, and wind-induced cooling. Mass transfer in SGSPs works mainly by molecular diffusion through the passage of salt from one layer to another, which tends to dissipate the salinity gradient with time. Ion penetration to the NCZ may induce the destruction of the interface [6]e. The interface, if severely impaired, leads to convective mixing and rapid heat loss from the LCZ. Among others, the flow dynamics play a dual role in the behavior of a SGSP. With regard to uniform temperature distribution and efficient heat extraction, the controlled convection within the LCZ is beneficial, while flow instabilities in the NCZ are detrimental to stratification stability and entire pond efficiency [7]. External factors like wind stress, diurnal temperature variation, rainfalls, and heat extraction rates add to the complexity of what is happening within the internal flow fields.

To optimize the SGSP design parameters, including the pond depth, the NCZ thickness, the salinity gradient profile, and the operating conditions concerned, the understanding of coupled heat-mass-momentum transfer mechanisms is absolutely essential. Experimental studies often are also expensive, time-consuming, and site-specific, and this is particularly true in the case of their full-scale applications [8]. Thus, analytical and numerical approaches gain much ground for the systematic analysis of flow behavior and transport phenomena in SGSP.
Numerous experiments and simulations have been conducted over the past five decades to investigate the natural thermal behavior of the region. Numerical simulations became very popular and versatile because they offered a wide range of inputs and outputs that could help predict the deduced behavior from experiences of salt gradient ponds more systematically [9]. Experimentally based pond calibration may further validate model predictions, which are comparatively less uncertain due to completely known initial and boundary conditions that are inherent limitations for experimental techniques. This simulation study started with minor errors suggesting that the surface area of the solar pond could grow in time. Considerably used for simulating dynamical behavior SGSP under steady-state and transient. With the development of CFD tools, researchers could now visualize velocity fields, temperature contours, salinity distributions, and heat fluxes across the layers of the pond, and which displaying the frontiers with an increased level of space and time resolution [10].

Concept of Solar Ponds

Solar ponds are unique solar thermal systems, combining solar energy collection and thermal energy storage in a single body of water. They use the salinity gradients that produce density differences to suppress natural convection and allow for heat accumulation in the bottom layers [9]. This stored thermal energy could be employed in power generation and low-temperature applications. Figure 1 represents Salinity Gradient Solar Pond (SGSP)

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Figure 1: Salinity Gradient Solar Pond (SGSP [63]

This is even more significant in skimming flow suppression and convective stability within the NCZ, determining the heat storage efficiency of the LCZ, and scrutinizing the influence due to design and operating parameters such as gradient thickness, boundary conditions, and heat extraction rates [11]. The superiority of simulation-type studies lies in parametric and sensitivity analyses, permitting the designer to run through numerous designs unhampered by physical experimentation. Simulation gives witnesses for model validation and scaling, bridging the gap between laboratory-scale experiments to large field installations. More recent developments include multiphysics modeling in which evaporation, radiation, and atmospheric interactions are considered, and transient and three-dimensional simulations that capture the full effects of reality [12]. Further trends are incorporated, as well as data-driven and machine learning techniques. These integration techniques are aimed at improving prediction accuracies and diminishing computational costs. Despite such advances, there are still many difficulties in accurately modeling the long-term behavior of the pond, turbulence transition, and more importantly in coupling the effects accurately. However, numerical simulation remains central to different SGSP boosting technologies because these simulations furnish the scientific basis for design optimization, performance prediction, and reliability assessment [11]-[12].

II. FUNDAMENTALS OF SALINITY GRADIENT SOLAR PONDS

Salinity Gradient Solar Ponds (SGSPs) are solar thermal systems that collect and store solar energy by maintaining a stable salinity-induced density gradient. This gradient suppresses natural convection, allowing the pond to trap heat efficiently in its lower layers for long-term thermal utilization.

The salinity gradient solar pond (SGSP) can be partitioned into vertically three distinct zones, each of which plays an important role in the maintenance of the thermal performance and stability of the pond. The Upper Convective Zone (UCZ) is the uppermost layer with low, almost uniform salinity [13]. It experiences free convection, which is the air movement, evaporation losses, and surface heat losses, caused by the wind directly felt by the UCZ. Due to this convection process, the upper convective zone remains at atmospheric temperature to contribute to a very minimal extent to the heat storage of the system. Below the UCZ and above the Gradients Zone (also known as the Non-Convective Zone, or NCZ) is the lower convective zone (CFZ). This zone displays a continuous rise in salinity with depth, thereby providing a stable density stratification. The NCZ is the most important zone in the pond in that it prevents buoyancy-driven convection and serves as a thermal barrier of insulation between the upper and lower zones. The Lower Convective Zone (LCZ) is described by a challenging but ineluctable level of salinity. It absorbs radiation and acts as a primary energy storage region [14]. Along with convection, built-up heat from the LCZ ensures a uniform temperature and guarantees effective heat extraction.
Salinity stratification is the key to the successful operation of an SGSP since, by definition, there is a stable increase in fluid density with depth. The density of pond fluid depends both on temperature and salinity; temperature gradients would destabilize the system by inducing convective buoyancy forces while the salinity gradients counteract the destabilization with an increase in density in the lower layers [15]. Stability is attained when the benefits of salinity that stabilize the resolution culminate in greater consolidation of the system, overcoming a lesser amount of instability caused by temperature. Double-diffusive thumbs rule must be assessed for stability, due to the fact that heat and salt have distinct molecular diffusivities or molecular mixing processes. The rapid diffusion of heat relative to salt implies that an improperly designed gradient situation can lead to local instabilities. Stability criteria using non-dimensional parameters such as the Rayleigh number, density ratio, and Lewis number generally are employed toward this purpose. A more appropriate approach is to create sufficient salt gradient causing very little internal convection and heat loss [16].
The phenomenon governing the thermal behavior of the Gradient Pond consists of simultaneously active transfer processes of momentum, heat, and mass. The solar radiation absorption heats the water, the temperature redistributes the heat, and mass is moved under strict molecular diffusion, thereby dissipating the falling gradient. Buoyancy forces as a result of temperature and concentration differences drive fluid motion, whereas various surface processes including evaporation, radiation, and shear due to wind affect upper-layer dynamics. Their complex interaction therefore determines the thermal efficiency-physical stability of STR and the long-term performance of SGSPs.

III. FLOW AND TRANSPORT PHENOMENA IN SGSP

The flow of transport phenomena within a salinity gradient solar pond are in a state of complex interplay: fluid mechanics, heat transfer and salt diffusivity condense within them. They are designed to minimize convections on a massive scale; instead, small scale flows still happen owing to the mechanisms of heat conduction, osmotic diffusion, and external disruptions. These affect direct efficiency of thermal storage and stratification stabilities. Perception of the internal circulatory patterns along with transport mechanisms and how they evolve with time is necessary to predict the performances of the pond with the view of minimizing heat losses, thereby guaranteeing optimum functionality on a long term basis under various environmental and operational conditions [17].
In SGSPs, natural convection occurs due to the varying densities generated by temperature conditions, which, in general, destabilize the system. To counteract this, a vertical salinity gradient is established in the non-convective zone, where densification increases with depth. This stabilizing stratification by salinity suppresses buoyancy-driven convection and prohibits light, warm fluid rising [18]. The strength of the--stabilising effect on the convection depends on the thickness of the salinity gradient. Therefore, sufficient thickness and efficiently preserved distribution for the salinity gradient are critical if the convection is to be suppressed. Any reduction in the gradient due to diffusion, mixing, or external force leads to a deconstricted disintegration in the suppression of circulation, resulting in additional heat losses and decreased pond efficiency.
On the basis of competing thermal and solutal buoyancy forces, it is the buoyancy which drives the flow in SGSPs. High temperature in lower convective zone promotes an upward buoyant motion. The increase in salinity increases the fluid density leading to a very stable confined circulation. On the contrary, incorrect salinity dissimilarity can initiate double-diffusive convection, resulting in stratified or oscillant flow fields within the NCZ. These currents enhance mixing

mechanisms and speed up the transport of heat and salt across the layers. The true categorization of buoyantly driven behavior is of primary importance for proper design specification for ponds to guarantee thermal stability during different solar and operational phases [19]. Heat transfer and mass transfer are inherently related by different processes occurring within the stratification. Because of the absorption of solar energy, the temperature of water increases, while the diffusion of salt simultaneously affects stratified density. Heat moves around more quickly than salt does, especially if the gradient of salinity is too insignificant. Such coupling results in a change in temperature and concentration shape through space and time. Efficient working from the point of view of heat includes forcing mass transfer that would not be desirable and controlling heat extraction from this LCZ. The numerical modeling of the combined transport processes serves as an indispensable tool for the meaningful forecast and design of stratification over a long period [20]-[21].

IV. MATHEMATICAL MODELING OF SGSP

Salinity gradient solar pond (SGSP) modeling provides a fundamental framework for treatment of fluid flow, heat transfer, and salt transport in the pond system. Due to the coupling between momentum, thermal energy, and solute concentration, the modeling is quite complex from a mathematical standpoint [22]. Generally we consider a system of coupled conservation laws conducive to predicting temperature distribution, velocity fields, salinity stratification, and overall thermal performance under a variety of environmental and operational circumstances.

The equations of motion comprise the continuity equation for incompressible flow, the Navier-Stokes equations for momentum conservation, the heat-transfer equation for the energy, and the mass-transfer equation for the salinity. The momentum equations hold for continuously compressible fluid components incorporating viscous effects and buoyant forces due to temperature/salinity gradients [23]. A feedback from salinity is also inserted into the energy equation through conductive and convective heat transfer, and heat generated inside the canal due to solar radiation absorption. The species transport equation is representing the salt concentration dynamics through convection and molecular diffusion, a requisite for the stratification stability analysis over the long term.

To simplify the analysis while keeping physical accuracy, the Boussinesq approximation is commonly used. This approximation was proposed for the effect of buoyancy in momentum conservation, with the assumption of constant fluid density otherwise [24]. This is perfect for SGSP's because small variances in density are the predominant force behind buoyancy-driven flows. The approximation is intended to greatly reduce computational effort, but at the same time to capture well thermosolutal convection phenomena.

Boundary conditions and initial conditions are vital for implementing a realistic Solar-Gas-Solar-Pond (SGSP) modeling. The pond-facing boundary condition often describes convective heat loss and radiation; evaporation effect and forced shear due to winds are paramount; sidewalls and bottom of the pond are usually either prohibitive or have a preset loss of heat. No-slip velocity conditions are required at solid boundaries and continuity of heat and mass transport across the interface between different layers [25]. The initial conditions describe the initial temperature and salinity profiles, often those corresponding to a condition of perfect stratification. Altogether, these parameters set the foundation necessary for a comprehensive numerical simulation and performance assessment of SGSPs.
Transmissivity τ_a based on absorption can be been calculated using beam intensity incident normally on the top layer and beam intensity absorbed by lower layer and the sum of four exponentials as given equation.

$$\tau_a = \sum_{j=1}^{4} A_j \, e^{-K_j x} \quad (1)$$

Where: x = Depth of water, A_j & K_j = constant

A1= 0.237, K1 = 0.032 m-1 for 0.2 < λ < 0.6 μm
A2= 0.193, K2 = 0.45 m-1 for 0.6 < λ < 0.75 μm
A3= 0.167, K3 = 3 m-1 for 0.75 < λ < 0.9 μm
A4= 0.179, K4 = 35 m-1 for 0.9 < λ < 1.2 μm

Calculation of Transmissivity alternatively

$$\tau_a = 0.36 - 0.08 ln.x$$

If the radiation is not incident normally,

$$\tau_a = 0.36 - 0.08 ln \frac{x}{\cos \theta_2}$$

Where x = depth of water in meter, valid for x >0.01 m

The movement of energy within the surface convective zone and the lower convective zone

The temperature distribution in a solar pond is computed by factoring in its three-zone structure. It would be appropriate to solve three separate differential equations-one per zone-where you need all interface matchings and boundary conditions of the pond's upper and lower surfaces to be satisfied with precision [23]-[24]. For the sake of simplicity, the more complex nature of the problem will be facilitated when the formulation assumes that both the upper convective zone (UCZ) and the lower convective zone (LCZ) can be regarded as perfect mixing layers with a uniform temperature characteristic that changes in exactly the same way as time.

Figure 2: Energy flow in and out of the surface convective zone and the lower convective zone

Allowing the pond to be much larger in its lateral dimensions compared to its depth L, under the assumption of temperature changes primarily in the vertical direction while preserving constant properties, the heat conduction problem for the non-convective zone may be expressed as follows.

Differential equation for the non-convective zone is the heat conduction equation of the form:

Solar radiation absorbed in the pond

$$\rho C_p \frac{\partial T_{II}}{\partial t} = k \frac{\partial^2 T_{II}}{\partial x^2} - \frac{dI}{dx} \quad (2)$$

$$I = I_b \times \tau_{rb} \times \tau_{ad} + I_d \tau_{rd} \tau_{ad} \quad (3)$$

Rate of useful heat extraction

$$T_{III} - T_a = \frac{\tau_r . H_g}{k} . \sum_{j-1}^{4} \frac{A_j}{K_{j'}} \left(1 - e^{-K_j{}' l_2}\right) - \frac{l_2}{k} . \frac{q_{load}}{A_p} \quad (4)$$

T_{III} = Temperature at the lower convective zone, T_a = Ambient temperature, τ_r = Transmissivity, H_g = Average global radiation , k = Thermal conductivity, A_j & $K_j{}'$ = Rabl & Nielsen constant, $K_j' = \frac{K_j}{\cos \theta_2}$ (5)

The symbol θ2 represents the angle of refraction, which correlates with an effective angle of incidence. This particular effective angle of incidence is chosen to precisely match the angle of incidence at the given point 14:00 hours on the equinox day, when the solar declination (δ) is zero, for the designated location under consideration.

l_2 = Depth of solar pond at the bottom of the non convective zone

$\frac{q_{load}}{A_p}$ = Rate of useful heat extraction

Transmissivity based on absorption at different depth of solar pond

According to Bryant and Colbeck:

Transmissivity when the radiation is not incident normally,

$$\tau_a = 0.36 - 0.08 ln \frac{x}{\cos \theta_2}$$

Transmissivity based on absorption for beam radiation

$$\tau_{ab} = 0.36 - 0.08 ln \frac{x}{\cos \theta_2}$$

Transmissivity based on absorption for diffused radiation

For the diffuse radiation take the angle of incidence θ_2 to be 60o

$$\tau_{ad} = 0.36 - 0.08 ln \frac{x}{cos \theta_2}$$

Overall thermal efficiency of the solar Pond

$$\eta_{th} = \frac{MC_p(T_{III} - T_a)}{A_{sur} H_g} = \frac{V \rho C_p (T_{III} - T_a)}{A_{sur} H_g} \quad (6)$$

Where M = Overall mass of the fluid stored in LCZ, C_p = Specific heat of the fluid stored in LCZ, A_{sur} = Total surface area of the pond.

V. SALINITY GRADIENT SOLAR PONDS: DESIGN AND DEVELOPMENT

In contrast to conventional stellarators, an experimental plasma was successfully sustained in the Hyundai accelerator at the National Fusion Research Institute in Republic of Korea. This experimental plasma involved the addition of ECW to a toroidal magnetic field that presented results on plasma stability, which was quickly initiated with the aid of elongation and triangularity. Plasma disruptivity lasted much longer due to the energy from LFS. Density and plasma heating are vital to achieving these results, while the plasma stored over 1 s against fusion puffs on magnetic islands. Peripheral heat conduction was proven to play a role in the recent SGSP performance study [2]. The study revealed a crucial role of heat losses through pond boundaries on the effectiveness of heat storage. Consequently, the simulations and respective experimental tests both demonstrated that insulating the edges did indeed maintain higher water temperature throughout the layers. The continuous display of temperature profiles under multiple arrangements stressed the importance of the boundary conditions and design configuration. Small modifications regarding the design were discovered to have considerable effect in the improvement of the overall performance, demonstarting that the control of heat conduction is crucial for optimizing SGSPs, particularly in variable weather conditions. System for monitoring SGSPs in real time was realized in [3] to keep track of temperature profiles and salinity gradients continuously. Early detection of the deviations leading to the dissipation of convection helps in ensuring stratification stability and thermal performance improvement. High-precision sensor data has helped in operation optimization and validated experimental observations. This study highlighted and laid down the importance of intelligent monitoring systems in conserving and efficient pond management in SGSPs, thereby adding significantly to SGSPs' performance and control in the long run. As explained previously in [4], experimental studies were performed on compact rectangular SGSPs to assess the temperature and salt concentration effects. The results showed that storage efficiency is predominantly influenced by pond size and stratification quality. The build-up of stable salinity gradients was highly effective in discouraging convection; thus, it enhanced heat retention. The temperature data confirmed the correctness of the models and provided useful experimental tools for designing and upgrading pond systems on a pilot scale. This information has direct relevance for research and industrial applications.

The thermal modeling of SGSPs was concerning the elimination of convection. This was discussed in [5]. The study had also contained... the use of salt gradients to augment thermal storage. The performance analyses of different pond geometries become informative as such to provide the optimal conditions for efficiency boost. These results all culminated to predicting the long-term performance of SGSPs by reinforcing the relevance of appropriate simulation to guide the practical implementation. There was also some regard put into combining SGSPs with hybrid power systems in [6], considering the coupling of working fluids for organic Rankine cycles. Comparison to the simulations testified to good heat integration performance, meaning improved thermal efficiency and power output. This study established the applicability of solar ponds in renewable thermal storage as appropriate to hybrid energy systems, complemented by advanced power generation technologies [7]. Inherent limitations arise when considering many environmental and operational factors that might be affecting SGSP efficiency. These problems, for example, could manifest from solar radiation, ambient temperature, and salinity, all of which are in some sense definitive of the relationship between pond behavior and environmental conditions. This study attempts to serve as background for estimating these kinds of parameters and also for evaluating the resultant performance criteria.

An experiment was conducted at [8] to investigate the effect of liquid covers on SGSP heat behavior under closed environment. The data from experiments showed that the application of liquid covers reduced evaporative heat losses, enhanced overall heat retention, and brought efficiency to both sides of the pond. Using liquid covers, the enhancement of overall efficiency through all levels of the pond indicates a simple yet effective option for improving foam chassis performance at different scales. Preparation for a transition from tunnel to the manufacture of water by SPSS had been taken up in (9). Hence, further research has been received, where it hath traversed its path of electric steals. According to new experience, SPSSs showed enhanced water distillation as compared to the conventional systems; thus providing evidence for the double functionality to the SGSPs for energy storage and water purification. The study pointed out about the effectiveness of the SGSP system in the renewable energy-water nexus for high suninsolation regions. Subsequently, equals were observed on the effective harnessing of large heat storage reserves created by SGSPs for the distillation of solar energy in very long periods(tabulated). Temperature distribution measurements and stability testing supported the outcomes on how to perform thermally. The study gave original and real-word information on editing and the functioning of that colliery, showing guidance to SBSP developers/stakeholders on small- and medium-scale installations.

As demonstrated by [11], thermal energy storage systems are feasible as far as SGSPs are concerned. Here, steady temperature profiles along with high heat retention reflected our assumptions in favor if their adoptability for the urban energy system. The observations could prevail upon the practical implementation of SGSPs with suitable efficiency ability in the long run. In a study by [12], efforts were made to make improvements in the SGSP thermal behavior through experiments in a model with multiple non-convective zones. From the data gained, local convective losses were substantially minimized and the resulting occasioned temperature stability and heat retention. The authors also put heavy emphasis on layer optimization as a strategy for design to help increase system performance. Mixed-mode heat extractions and realistic hydrodynamic performances of SGSPs were discussed in two places of work; one published in [13]. It pointed out the severe limitations asociated with simplified models, emphasizing representations of convective zonations, as well as non-convective zones. The simulation results matched well with the experimental data and offered a basic trend in the development of predicting energy-extraction efficiency.

Layer thickness (dz) and heat losses from different zones have been examined in a study [14]. By increasing dz values, less heat losses and better stratification stability were found. A quick look at Figure 16 shows how optimization in design leads to better performance in terms of energy storage. An environmental life-cycle assessment for a prototype SGSP plant was carried out in [15]. The report highlighted that SGSPs are an energy source that paves the way for a sustainable energy supply with the least possible ecological impact. This tenders a further argument concerning green energy applications. [16] effects have been characterized and a computational fluid dynamics model has been used to investigate the simultaneous influence on heat and mass transfer. The result showed that these parameters affect realistically the thermal storage efficiency and stratification stability. This, then, necessitates the more advanced coupled modeling problems. In [17], we presented climate-specific modeling of SGSPs, focusing on double-diffusive convection and the influence of the environment on thermal performance. These findings support the adaptive design strategies for the areas according to climate. In [18], SGSPs were combined with solar stills to enhance productivity. Experimental and modeling results revealed that heat utilization and desalination efficiency are enhanced due to the use of SGSPs. In [19], the comparative experimental study on permeable and non-permeable SGSPs was discussed. It was concluded that such systems' heat retention is significantly influenced by soil permeability, thus emphasizing the choice of materials for pond construction. Finally in [20], some parametric simulations examined the effects of Soret and Dufour. The results showed their significant impact on temperature stratification and energy retention, thereby contributing to the new high-efficiency design of SGSPs and multidisciplinary models.

Table 1: Thermal Performance and Operational Studies of Salinity Gradient Solar Ponds (SGSPs)

Ref	Focus / Objective	Methodology	Key Findings / Contributions	Limitations
[1]	Thermal performance of SGSPs	Finite element modeling of temperature distributions	Salinity stratification suppresses convection, enhances heat storage; pond geometry and boundaries affect efficiency	Focused on modeling; limited experimental validation
[2]	Impact of peripheral heat conduction on SGSPs	Modeling and experimental analysis	Lateral heat loss reduces storage efficiency; insulation improves retention	Did not consider long-term environmental effects or operational variability
[3]	Real-time monitoring of SGSPs	Sensor-based monitoring of salinity and temperature	Continuous monitoring improves stability; supports operational optimization	Limited to small-scale demonstration; did not assess long-term durability
[4]	Temperature and salt concentration behavior in compact SGSPs	Experimental investigation	Geometry and stratification affect thermal storage; stable salinity prevents convection	Focused on small-scale ponds; scalability not analyzed
[5]	Thermal potential and operation of SGSPs	Simulation modeling	Salinity gradients maintain lower zone stability; pond configuration impacts energy retention	Model assumptions may oversimplify real-world conditions
[6]	Integration of SGSPs with ORC and LNG cold energy	Thermodynamic modeling and feasibility analysis	Hybrid system enhances thermal efficiency and power generation	Simulation-based; no experimental validation
[7]	Operational and environmental factors in SGSPs	Multivariate statistical analysis	Environmental conditions influence thermal efficiency; guidelines for operation	Focused on analysis; did not propose specific design improvements
[8]	Effect of liquid cover on SGSP performance	Experimental study	Liquid cover reduces evaporative losses; improves retention	Limited to controlled conditions; long-term performance not studied
[9]	Solar distillation integrated with SGSP	Experimental development and testing	Hybrid system improves freshwater production and heat utilization	Pilot-scale study; economic feasibility not analyzed
[10]	Experimental SGSP for heat storage	Construction and monitoring of temperature layers	Validates theoretical models; demonstrates stable stratification	Small-scale pond; field scalability and environmental effects not evaluated
[11]	SGSPs for thermal energy storage in Pakistan	Experimental evaluation	Significant heat retention; supports regional deployment	Limited to one climate; long-term operational effects not assessed
[12]	Enhanced SGSP with additional non-convective zones	Experimental study	Modified design reduces convective losses; higher lower-zone temperature	Limited range of pond sizes; durability over time not evaluated

[13]	Gradient layer heat extraction	Realistic numerical modeling	Improved thermal performance prediction; guides design	Model-based; experimental validation limited
[14]	Effect of non-convective and lower convective zone thickness	Experimental analysis	Optimizing layer thickness improves retention and stability	Focused on specific layer configurations; environmental variability not included
[15]	Environmental assessment of pilot SGSP plant	Operational and environmental analysis	SGSP provides sustainable energy with minimal ecological impact	Pilot scale; limited economic analysis; full lifecycle assessment not included
[16]	Soret and Dufour effects on SGSP	Numerical simulation	Heat and mass transfer influenced by multi-physics effects; improves efficiency	Only numerical; experimental validation lacking
[17]	SGSP modeling under Moroccan climate	Numerical simulation with double-diffusive convection	Climate-specific modeling improves prediction; guides design adaptation	Specific to Moroccan climate; results may not generalize globally
[18]	Enhancing solar still yield with SGSP	Literature review	Integrating SGSP improves freshwater production; highlights design importance	Review-based; lacks new experimental data; practical deployment challenges not addressed
[19]	Permeable vs non-permeable mini SGSPs	Comparative experimental study	Pond material and permeability affect temperature and retention	Limited to mini-scale; scalability and long-term effects not assessed
. [20]	Soret and Dufour effects on heat and mass transfer	Numerical simulation	Coefficients affect storage efficiency; informs high-performance design	Only numerical; experimental verification needed; limited pond sizes analyzed

VI. HEAT TRANSFER MECHANISMS IN SGSPS

Plant laboratory experiments meant on temperature stratification and turbidity characteristics of miniature solar ponds were indicated in [21]. It experimented with the real quantification of the enhancement effort on small solar ponds; using a more elaborate system such as baffle systems, absorptive surface coatings, and good insulation systems can facilitate better separation of cold and heated layers with high efficiency. Measuring the temperature layer-by-layer throughout the entire experimental duration points to the substantial savings in thermal energy storage due to minimized convective losses. It reveals the real-life solutions as powerful and effective tricks for the augmentation in the performance of mini SGSPs, thereby making it possible.

The study in reference [22] discussed an uncertainty-averse, Bayesian active learning method for molecular dynamics simulations in phase transformation and thermal conductivity problems. While the particular application of this study was not of solar ponds, it has demonstrated a much improved capability of prediction and reduction in computational cost owing to uncertainty quantification. The probabilistic-based method offers a broader new exciting area for understanding, which in particular could be extended to thermal transport simulations in stratified or layered energy systems like SGSPs, where the uncertainty issues of the heat transfer prediction necessitate attention.

One case study of a one-step hybrid computational fluid-dynamics and thermal-hydraulic analysis for the purpose of optimizing heat transfer and flow control is presented in Ref. [23]. The height of the thermal uniformity and the heat transfer coefficient, thought to significantly improve through optimal control strategies, has been developed. Even though it belongs to a different thermal system, model approaches and thermal management techniques are applicable for the SGSP applications, focusing not on thermal but on well-controlled thermal states and storage models.

An experimental manipulation of the heat and mass transfer in a salt-gradient solar pond from a controlled period of irradiation was performed in [24]. Working on the temperature distribution and salinity profile, the analyses concluded on the efficiency of heat storage. In numerical simulation, a good fit was found between the trends in prediction and the knowledge from the experiments. This estimation of thermal stratification and prevented convective currents validated the numerical model better. Even if our study is subjected to a further constraint in respect to this optimal present being an engineer, in the direction of establishing a simulation value experimentally, we could still gain better point estimates by reduction of the burstiness.

The thermal-salinity modeling and the stability performance of pilot-scale SGSPs incorporating phase change materials were investigated in [25]. Results prove that integration of PCM considerably improves the energy storage capacity, reduces the magnitude of temperature fluctuations, and enhances the layer stability. The study, limited to a successful pilot-scale validation and possible scaling constraints in the exercise, nevertheless demonstrated exciting ways in which PCMs help in improving the thermal performance of SGSPs and in maintaining their long-term stability.

Soret and Dufour convection were simulated in SGSPs in the context of double diffusion. The preliminary discussion was initiated in [26] in pure double diffusion scenarios. Numerical simulations demonstrated that the Soret and Dufour effects have a major influence on the heat and mass transfer rates and overall storage efficiency. This study finalizes the need to invoke multidisciplinary effects for correct SGSP modeling, in spite of any limitations posed by idealized boundary conditions and the lack of in situ experimental validation.

In a study published in [27], a numerical analysis was supplemented with experimental studies in the case of double-diffusive convection in SGSPs. Although these additional considerations brought improvements in both the qualitative aspects of the predictions and hence their accuracy, the computational demand was considerably increased as well. Therefore, the paper attempted to analyze the recommend regular efforts to study this life dynamically trade-off regarding both criteria, thus giving a solid set of recommendations for future work on best practices for prediction of SGSP performance, although mainly related to limitations pertaining to scale and experimental constraints dictates.

[28] applies a rather detailed summary to the design, performance, operations, and applications of solar pond systems. Key details on performance parameters, thermal storage efficiency consideration, and environmental information are provided together with the descriptive nature of the review. Although the review is primarily intended to be used as a reference for renewable energy systems' design and application contexts, it also offers some insight into solar ponds.

Review [29] highlighted employment of solar ponds, drawing upon the works for improving on new trends of technological opportunities and potential energy efficiency and standardization in thermal energy storage systems. Little experimental evidence was presented, but the review outlined visionary ideas for development in the field of recovery of low-grade heat and unconventional SGSP applications.

A study [30] analyzing the phase-change thermal behavior during controlled freezing conditions was discussed in the last place. The article is opportunely addressed to a series of materials and food applications, which gave indirect insight to the influence of phase behavior, heat transfer, and temperature-induced sensitivity mechanisms on potentials for phase change material integration and thermal storage analysis in SGSP systems.

VII. CONCLUSION AND FUTURE WORK

This review has presented a comprehensive synthesis of the fundamental principles, flow dynamics, and thermal performance assessment of salinity gradient solar ponds (SGSPs), with particular emphasis on numerical simulation and experimental investigations. The analysis has shown that SGSPs' efficiency is heavily reliant on the salinity's rather stable stratification to overpower natural convection and promote long-term heat storage in the lower convective zone. Flow behavior within the pond is driven by the coupled processes of transfer of heat, mass, and momentum; the slightest disturbance tends markedly to affect thermal efficiency and stratification stability. It can be seen from various experimental and numerical studies that numerical modeling accompanied by computational fluid dynamics has played an instrumental role in grasping the internal flow structures, temperature distribution, and salinity evolution, under different climatic and operational conditions. The experimental studies ultimately corroborated the model and demonstrated the importance of the pond geometry, boundary condition, insulation strategy, and layer thickness on the thermal performance of the system. Experiments on key design parameters like geometry of the pond and the surrounding terrain support the numerical and experimental study results. Developments in numerical modeling, material integration, simulations involving mass transfer, and deployment of cost-effective applications will help concretize future endeavors into the effect of phase change on the thermal behavior of the system through numerical modeling. Recent advancements, such as integrated multiphysics modeling, use of phase change materials, and real-time monitoring systems, have greatly improved predicted performance, reliability, and, thus, have firmly stamped their acceptability not only as a possible measure for solar thermal energy storage but also for several other applications as well.

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