CFD-Based Flow Simulation and Heat–Mass Transfer Analysis in Salinity Gradient Solar Ponds

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Abstract:

Salinity Gradient Solar Ponds (SGSPs) had been an appealing manner for solar thermal energy compounding at modest prices and long-term heat storage. This paper is intended to clarify the fact, and draw attention to the numerical and Computational Fluid Dynamic (CFD) explorations—in actions that do not terminate—as to means of improving the thermal dynamics of solar ponds by design morphing and using heat-transfer systems, considered advanced. Run first of the mathematical modeling aimed at giving an appraisal of the solar radiation components—beam, diffuse, and global radiation—with accounting for transmissivity losses resultant of reflection, refraction, and absorption, as effects are managed by the local climate contours. The thermo behavior of the three-zone solar pond, which comprehends the Upper Convective Zone (UCZ), the Non-Convective Zone (NCZ), and the Lower Convective Zone (LCZ), is approached by energy balance equations. Three-dimensional CFD simulations were carried out using ANSYS Fluent to evaluate different solar pond types: a conventional solar pond single type without internal heat extraction tubes terminated at the bottom one-third of the pond depth below the water surface, a solar pond type with internal serpentine tubes for extracting thermal energy, and a helical coil heat transfer type solar pond. The simulations also took into account the coupled heat transfer, species transport, and buoyancy driven flow with realistic boundary conditions. The heat transfer mechanism in the system was a nanofluid quanta along with saline water as the transfer media would be used to assess thermal storage properties. Validation of modeling is done based on experimentation or published data revealing good matches as within maximum temperature differences of less than 1%. This suggests that solar pond arrangements with heat extraction tubes integrated into the pond mass contribute significantly to improved heat distribution and storage efficiency compared to conventional solar ponds. Helical tubes stand tall in this regard thanks to their better heat extraction and combined diminished thermal stratification losses. The results served to conclude that the shape and size of the geometrical domain, in conjunction with nanofluid usage, substantially enhance the overall performance of solar ponds for energy application with renewables.

Keywords: *Solar pond, Salinity gradient, CFD analysis, Thermal energy storage, Nanofluids, Heat extraction, Renewable energy*

I. INTRODUCTION

Fossil fuel reserves are being continuously decreased so at the same time, there is an urgent need to consider environmentally cleaner and sustainable documents for the future energy transition [1]. Renewable energy could save a dying planet by responding to call for electricity with solar, hydro, wind, geothermal, and biomass, all of which help the world get rid of greenhouse gases, with much less environmental interference and prolonged energy availability in some expected scenarios to meet future energy requirements [2]. Figure 1. represents Renewable Energy.

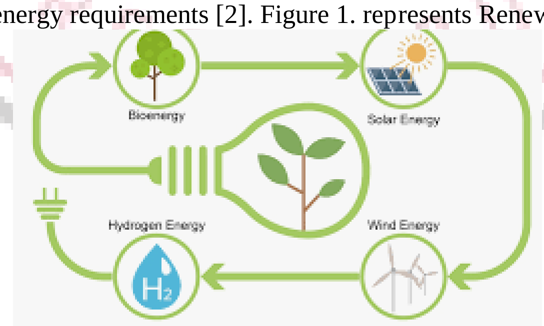

Figure 1: Renewable Energy [21]

Global energy demand and sustainability challenges

Demand for energy globally is increasing continuously due to population growth, industrialization, urbanization, and rising living standards [2]. Conventional energy systems that majorly depend on fossil fuels have caused grave environmental issues, including global warming, air pollution, and resource exhaustion. In addition, notable inequality among key energy resources raises concerns related to energy security and economic stability. In this context, sustainable development reminds that energy systems must be environmentally benign, economically viable, and socially accepted [3]. Renewable sources of energy are rallying support for research and development in a bid to have a sustainable, clean, and secured energy supply for present and future generations.

Role of solar thermal energy in clean power generation

Solar thermal energy plays an important role in the generation of clean energy. It directly converts radiative solar energy into useable thermal energy. Unlike the photovoltaic system, the solar thermal technology can collect, store, and actually utilize heat power [4]. The likes of solar collectors and solar ponds also offer integrated storage systems for solar thermal energy and its capability for working even without sunshine [5]. Solar thermal energy is a vast resource that produces minimal emissions during operational use, ensuring that the energy produced by solar thermal power plants is renewable and environmentally friendly. The scalability of solar thermal energy and its potential in hybrid systems underline its relevance in reducing reliance on fossil fuels and increasing sustainable energy infrastructure, particularly in high-insolation areas [3]-[4]. Figure 2 represents solar thermal energy

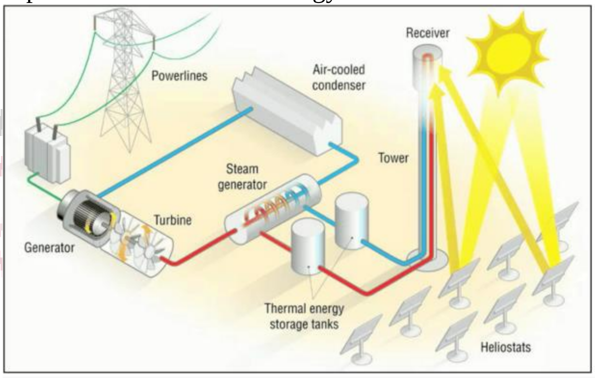

Figure 2: solar thermal energy [22]

Overview of Solar Energy Utilization

Solar power is the use of irradiation from the sun to produce either electrical or thermal energy for various applications. Solar energy boasts promise as being amongst the top alternatives to conventional systems of energy due to its profusion and renewability [5]. Solar technologies can be distinguished according to their energy conversion mechanism, application scale, and storage capabilities; and, thus, they are useable in both system sizes, i.e., the decentralized and centralized energy systems [6].

Direct and indirect solar energy conversion

Solar energy conversion is an array of two classes, the direct conversion, and indirect conversion of the solar energy. In a direct conversion, solar radiation is directly transformed into the usable forms of energy like electricity through photovoltaics or heat from solar collectors [7]. Indirect conversion makes use of solar energy that has been converted into other energy forms such as wind, biomass, or hydrology. On one hand, direct conversion systems tend to yield relatively high efficiency and maintainability, and, on the other, indirect systems provide a wide range of energy potential and greater storage that is sustainable for the long term. Thus, in the context of increased diversity in the renewable energy mix, direct and indirect systems contribute to overall sustainability of energy [8].

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.

The solar pond refers to a large-scale thermal reservoir using a stratified saltwater system to absorb and store solar energy. It works in part by creating a salinity gradient from up-to-down; warm water is pushed by the convective cells to rise above the cold and heavy water. The highest heating is in the puddle through the absorption of solar radiation through water that rises and warms the puddle's bottom [10]. Due to high salt concentration and density, he launched very warm water to be trapped and allowed storage of considerable thermal energy. The so-called pond usually has three regions: an overlying convective region, an intermediate, non-convective, or transitional area, and a lower convective zone, which play crucial roles in its thermal stability and storage [11].

Solar ponds' concept dates back to the early twentieth century with some initial observations of natural saline lakes with better temperatures at the bottom. Systematic research and development activity began in the 1950s and 1960s, which focused on the controlled formation of salt gradient for practical energy extraction [12]. The significance of solar ponds came to light during the global energy crisis in the 1970s, and it served as a platform from which pilot domains like solar ponds were established in countries such as Israel, the United States, and India. Improvements in the design of the pond structure and salt handling and thermal extraction methods since then have been aimed at increasing efficiency and reliability through applied work. Most current research studies performed numerical modeling and flow simulation to optimize performance and evaluate actual operational difficulties [13].

A Salinity Gradient Solar Pond (SGSP) is a solar pond type uniquely developed to effectively collect and store solar thermal energy by maintaining a stable salt concentration gradient right along its depth inside the pond [14]. Unlike with conventional solar ponds, design of the SGSP is such that convectional heat losses are minimized, and the lower region of the SGSP can therefore get heated to and retain considerable temperature for extended periods. The controlled salinity

gradient maintains-co-functions in this system[15]. Energy absorption and storage are achieved simultaneously through a single SGSP. This concept supports SGSPs which are however simpler, cheaper, and provide thermal storage and hence make their application in low-grade power generation, industrial heating, and desalination particularly plausible [14]-[15]. An increase in salt concentration along a slope between the top and bottom of the pond gives rise to a density gradient, which is essential to the concept of a solar pond. The heaviest and most saline water finds itself at the bottom whereas the lighter and less saline water accumulates near the surface. Salinity gradient inhibits buoyancy-driven convection when heating by solar radiation [16], thereby suppressing vertical mixing. Such stable stratification allows heat to concentrate in the lower convective zone without any major heat loss to the up. Salinity gradient is normally managed through controlled salting and diffusion management to ensure the continued thermal stability. Understanding and modeling this gradient helps immensely in representing the flow behavior and heat transfer characteristics of an SGSP system [17].
The problem of salt stratification assumes importance in respect of the heat-storage capacity within salinity-gradient solar-ponds. In fact, stratification aids the prevention of natural convection. It slows losses of heat from lower and hot layers to the upper and cold layers and levels of ambient temperature in the process [18]. This in return allows the lower convective zone to rise to temperatures significantly higher than those attained in non-stratified bodies. Effective salt stratification allows for large thermal efficiencies in ensuring a stable non-convective zone that acts as an insulating layer. Any disturbances or degradation, through mixing, will lead to reduced temperature gradients and will degrade the energy-storage performance [19]. Therefore, maintenance of salt stratification is the imperative towards long-term operational efficiency. Numerical flow simulation and evaluations help in understanding stability of stratification and optimization of design-pond parameters towards maximum heat-storage performance.

The salinity gradient solar pond consists of three areas that are functionally divided based on salinity, density, and thermal characteristics. These work with each other in absorbing, storing, and holding the solar energy by controlling fluid flow and heat transfer within the pond, and keeping thermal stratification and energy storage most efficient [20].

Upper Convective Zone (UCZ)

The Upper Convective Zone (UCZ) is the topmost layer in a salinity-gradient solar pond where near or low concentrated salt water prevails. This region is directly in contact with the atmospheric conditions, and hence, significant heat losses take place due to evaporation, convection, and radiation [21]. Natural convection occurs freely within the UCZ, as it is homogenous in salinity, causing the temperature distribution to be nearly uniform. The UCZ might not play a significant role in heat storage, but it protects the lower layers efficiently against external assaults of surface-cooling effects and wind-induced mixing.

Non-Convective Zone (NCZ)

The non-convective zone (NCZ) is positioned amidst the upper and the lower convective zone. A deeply steep solute gradient develops where stable saltwater density stratification keeps any convective instability at bay due to temperature gradients [20]-[21]. It behaves like a thermally insulating barrier, thereby stopping any heat endeavor from heading upward from the lower convective zone to the surface. Its stability is of great importance in keeping much heat inside by preventing mixing from any changes in stratification and hence significant thermal losses. Accurate modeling of this is essential for flow simulation in solar ponds with salinity gradients [22].

Lower Convective Zone (LCZ)

The Lower Convective Zone is the bottommost layer of a solar pond having very high salt content and fairly uniform salt concentration. It absorbs most of the incoming solar radiation and serves as the primary thermochemical zone in thermal energy storage [23]. This storage is quite comprehensive because the very salty and dense liquid in this layer is imprisoned, resulting in high temperatures. At this point, convective heat transport moves throughout the entire LCZ, ensuring a uniform distribution of temperature. This becomes a crucial part of the SGSP then, as thermal energy loaded into this zone can be used for the generation of power or industrial heating [22]-[23].

II. RELATED WORK

The initial global study on salt-gradient solar ponds appeared incomplete, considering no enumeration of experimental data and quantitative assessment of performance. Nonetheless, they do provide an important background of insight into the development of SGSP technology.T he other experimental studies were characterized by salt-free solar ponds so as to exhibit the behavior of temperature distribution and heat storage; this implies that the design of cheap thermal storage is still a pending approach currently for local applications [3]. The results remain limited somewhat as these studies were performed for small dimensions and simple environment conditions, but nevertheless the point should be quite promising for decentralized storage of thermal energy. The role of SGSP systems in conjunction with various renewable energy sources was chosen with their investigations into the integration of renewable energy and thermal energy, but further analysis revealed new insights into the possibility of incorporating new, environmentally viable energy resources. These studies shed light on some potential synergies and efficiency gains for hybrid systems, but they reflected the need for more rigorous testing of promising technologies. Material centered studies disputed the stabilization mechanisms of high internal phase complex emulsions that acted as secondary contributors in the characterization of transport properties in high thermal conductivity filled polymer-based composite materials, thereby offering indirect insights for the advancement of thermal interface materials in the context of energy storage [4]. In summary, the study did not intend to establish its relationship with SGSPs directly; rather, it contribute to the fundamental understanding of composite behavior when exposed to thermal loading and thus may contribute toward the aspect of design of thermal storage.Therefore, efforts were made to look for some strategies in designing and constructing it experimentally. Major issues were layer stabilization techniques, construction strategies, and early-stage thermal performance requirements [5]. Although further performance data were needed to be generated over considerable periods, these experiments have nevertheless offered useful guidelines for putting solar ponds into direct operation. The reviews of storage systems for renewable energy exclusive to thermal energy strongly underlined integration schemes, methods to increase efficiency, and applications of SGSPs in hybrid energy systems [6]. A lack of experimental validation is one of the main disadvantages linked with these works; Statistically, they go to show that SGSPs will have future relevance in modern renewable energy infrastructure. The study of natural polymers and polysaccharide based materials suggested energy-material interactions that on a molecular level established a subset of material level energy storage mechanisms. This whole specialized view of such studies are at the very forefront in the construction of advanced storage media. Several configurations and models/assumptions have carried out a series of analytical and empirical investigations into the phase change dynamics processes, including melting and solidification. This has given rise to a focus on the mechanisms of convection and thermal transport in energy systems [8]; albeit primarily theoretical investigations, such considerations are significant for SGSP systems orchestrating phase change materials. Some outline reviews were summarized for advancements in solar energy-based pond technologies. Design changes and means of enhancing thermal efficiency are always emphasized with regard to such design of the pond [9]. The drawbacks provided become clear where experimental data in vast amounts were not made available; however, the reviews are excellent source material for research and ways to enhance the efficiency of the systems in the future. Experimental research in case of circular-type solar ponds that uses several alternative salt media shows a way to improve thermal stability and enjoys almost uniform maintenance of temperature [10]. While these cases certainly show improvements on a small scale involving the use of a specific material, it hints at ways to let SGSP systems have a better storage performance.

Table 1: Recent Advances and Experimental Investigations on Salinity Gradient Solar Ponds (SGSPs) and Thermal Energy Storage Systems

Ref	Focus / Objective	Methodology	Key Findings / Contributions	Limitations
[1]	Temperature and turbidity in mini solar pond with enhancement measures	Experimental study with baffles, coatings, and insulation	Enhanced thermal stratification and energy retention; reduced convective losses	Small-scale setup; limited long-term performance analysis
[2]	Uncertainty-aware thermal transport in SiC	Bayesian active learning molecular dynamics	Improved prediction accuracy and reduced computational cost; informs thermal transport modeling	Not directly SGSP-related; theoretical focus
[3]	Fluid flow and heat transfer in supercritical water reactor	Numerical simulations and control system construction	Optimized temperature uniformity and heat transfer efficiency; relevant modeling approaches for thermal systems	Reactor-specific; limited direct applicability to SGSPs
[4]	Heat and mass transfer under solar simulator	Experimental and numerical investigations	Validated numerical models; improved layer stability and energy retention	Experimental scale limited; idealized boundary conditions
[5]	Thermal-salinity performance with PCM	Pilot-scale experimental analysis	PCM integration improved temperature stability and thermal retention	Pilot scale only; scalability and long-term performance not analyzed
[6]	Soret and Dufour effects on double-diffusive convection	Numerical simulation	Multi-physics effects significantly impact heat and mass transfer	Lack of experimental validation; simplified assumptions
[7]	Double-diffusive convection impact on simulation	Numerical and experimental validation	Improved accuracy; computation time increased	Limited experimental scope; small-scale pond focus
[10]	Freezing effects on wheat starch proteins	Experimental analysis	Insights into phase changes and thermal effects; relevant to PCM/thermal systems	Food-specific; not directly SGSP-related
[11]	History and progress of SGSP	Review study	Summarized technological development, energy storage efficiency	Lacked experimental studies; no quantitative analysis
[12]	Miniature saltless solar pond	Experimental investigation	Demonstrated temperature retention and compact design potential	Small-scale; simplified environmental conditions
[14]	High internal phase Pickering emulsions	Experimental study	Hydrogen-bond-based crosslinking insights; applicable to thermal interfaces	Lab-scale; materials-focused, not SGSP-specific
[15]	Practical solar pond design	Experimental study	Provided construction techniques, layer stabilization,	Small-scale prototypes only

			and thermal performance guidance	
[17]	Polysaccharide effects on gut microbiota	Experimental study	Thermodynamic and molecular insights; potentially relevant for PCM research	Domain-specific; not SGSP-focused
[20]	Cylindrical SGSP with calcium chloride stratification	Experimental investigation	Stable temperature retention and improved storage efficiency	Single chemical focus; small-scale demonstration

Fluid Flow and Stratification Stability

Past numerical studies have elucidated that the addition of hybrid nano-structures to solar salt ponds significantly enhances heat transfer and thus causes better thermal stratification in the pond [11]. As it happens, on the combined effect of energy storage and convective heat loss substantially improved; however, these achievements remained partially validated during the experimental study and are contingent on numerical results. Nevertheless, it introduces a pathway to higher engineer cap-abilities for SGSPs. The work on the traingular SGSP by means of digital and experimental means has shown that in association with reflectors and glazed systems, there is a significant improvement in thermal collection and energy retention [12]. The optical enhancements strongly apppeared in small and medium scale ponds due to field constraints and geometric limitations. The study is important for optimizing pond geometry with surface modifications in order to improve insulation from heat. Opportunities in combining phase-change materials (PCMs) within SGSP are being explored through initial numerical optimization of PCM mass and its melting temperature [13]. Improvements in thermal behaviour and energy storing capacity have been exhibited, with validation experiments and further economic-to-afford studies being needed. The study guides to nullify the inclusions of PCMs into the solaria. A numerically oriented layered thermal management using solar still–solar pond systems for efficient water purification was conducted [14]. The incorporation of SGSPs enlarged heat flux and brightness productivity, but the results might be attributed as findings from pilots study and site-specific conditions. The overall analysis shows the potential advantages of combining solar pond systems with water treatment technologies. The effects of the dual stratification during MHD boundary layer flow through porous media were numerically investigated on the production from fluid velocity, temperature, and energy [15]. Though the study was primarily theoretical and founded on rather idealized assumptions, its results apply to the conceptual design of multilayer thermal mediums in compliance with the principle of SGSP. Field studies hold substantial importance in naturally stratified tropical lakes, especially for providing insights into heat retention and thermal stability in stratified regions; however, concrete conclusions from these studies are hard to come by due to the very site specificity of environmental conditions. It is worth telling that various mechanisms of natural stratification discussed appear to effectively operate under tropical climate. Field investigations of naturally stratified tropical lakes have provided insights into heat retention and thermal stability within stratified water bodies [16]. Although site-specific environmental variability limits direct application, the observed natural stratification mechanisms offer valuable analogies for SGSP operation in tropical climates.Studies on the influence of flow velocity and turbulence in solar collectors reveal that optimized flow conditions can achieve more uniform heating of the working fluid [17]. While direct validation for SGSPs is still required, these findings emphasize the importance of fluid flow dynamics in thermal storage and heat extraction systems.

Double-diffusive stability analyses of thermally stratified porous fluid layers with internal heat sources demonstrate complex convective behavior affecting system stability [18]. Though primarily theoretical, such models are useful for assessing the stability of salinity and temperature gradients in SGSP designs. Ebnet al. [19] reported the experimental field researches of thermally stratified aquifers under the warmening due to climate change, and concluded the high impact of stratification on energy and mass transfer. Costly though the results just look into one place and that is suitable for directing management strategy action to control stratification effects in SGSPs, and probably in relevant thermal reservoirs as well.Thus, thermal processes affect energy recovery and system efficiency, according to testings on effluent stabilization and treatment ponds during optimization studies. These general findings could offer some specific insights into the improvement of pond-based thermal control towards SGSP implementation.

III. RESEARCH OBJECTIVES

- Conduct mathematical analysis at chosen sites, assessing radiation, reflection, refraction, and transmissivity.
- Generate 3D CAD models for Computational Fluid Dynamics (CFD) examination of the solar pond.
- Utilize CFD analysis to investigate temperature fluctuations with varying water salinity levels and Al2O3 nano-fluid.
- Validate CFD findings, compute effective heat extraction rates, and ascertain the solar pond's overall thermal efficiency.

IV. RESEARCH METHODOLOGY

A solar pond is a pool designed with particular specifications geared towards gathering the sun's thermal. On the saline sea, a pond with lower salinity lies over a pond with higher salinity, thus creating vertical differences in salinity. Meanwhile, the degree of both concentration and density of the salt solution is continually increased with deeper levels. Beyond a certain distance, this mechanism maintains the concentration of salt within the solution fairly high.

Solar Radiation and Performance Analysis

The geometry of the sun is crucial in establishing the availability of and the design for solar radiation in any given area. Declination angle denotes the angular position of the sun with respect to the equatorial plane of the Earth and fluctuates through the year across the axial tilt of the Earth. The hour angle is able to describe the angular displacement of the sun from the local meridian and can consequently determine the position of the sun with respect to time during daylight. The zenith angle, separating the sun's rays from the vertical, governs the solar radiation intensity on the horizontal area of the solar pond. As simple as calculating data from the hour angles of sunrise and sunset will give a day length, it defines how long the sun shines on the pond surface, directly affecting the thermal performance of the solar pond. Estimation of the solar radiation components will benefit the thermal input of the solar pond system. Extra-terrestrial radiation infiltrates the outer limits of the Earth's atmosphere and serves as a baseline for radiative calculations. The global radiation collected by the pond surface is made up of the beam radiation that goes directly from the sun and the diffuse radiation reflecting from particles in the atmosphere. Hourly radiation studies enable capture of daily changes in solar intensity, while monthly radiation status values are used to evaluate seasonal variations. These yield reasonably good estimates for available solar radiation, which serves as the grounds for their utilization in optical, thermal, and CFD performance studies adopted for the solar pond. Shading losses from a solar pond are mainly caused by reflection/transmission (optical losses) and absorption losses occurred at the air–water interface and within the pond. When the solar radiation hits the pond, some portion of it gets reflected back to space after air–water refraction as per Snell's law. Transmittance of the pond water declines according to the depth of pond as a result of absorption both by the water and salts dissolved in it. Thus, the energy approaches downward, gets absorbed, and becomes gradually weakened. However, the incidence angle determines the two-fold loss of reflection and transmission; the higher the angle, the higher the reflection. Accurate quantification of these optical losses is a must to work out the amount of solar flux minus losses for thermal storage in the lower and hence convective layers.

Heat Transfer and Energy Balance Modeling

Numerical solutions for full-time heat transfer and radiation primarily in the upper convective regions, called UCR, non-convective region, and LCR were estimated by the use of energy balance equations. UCR and LCR are treated as well-mixed sections where the temperature remains uniform; heat exchange within the NCZ is mostly one dimension) conduction. Absorbed radiation leads to heat storage in the LCR, heat convection over the surface and through the bottom causes losses. Auxiliary heat-effusion speed is found based on the temperature differential between the LCR and the ambient environment. The fractional thermal efficiency is given by the ratio of directly utilized thermal energy to total solar energy impinging on the solar pond area.

Computational Fluid Dynamics (CFD) Modeling

A CFD model was set up for solar pond with the aim of analyzing heat transfer and flow behaviors for three configurations: nonconversion solar pond (design 1), a serpentine tube (design 2), and a helical tube (design 3). In CAD, this required the construction of the pond with all fluid geometry and sizes properly defined. Design 1 represents a straightforward divergence pond model which, in contrast to Design 2 and Design 3, incorporates buried heat exchanger tubes geared to accelerate thermal energy almost entirely out of the system. The present work was an attempt to map out the most critical versions due to parallel and potential impacts on comparison with other variables. The design is focused on the boundaries of the domain itself to explore, determine, and enable accurate simulation under heat and fluid-flows hence boundaries included free surface exposure and insulated sidewalls. The size of the domain was critically determined, eliminating edge effects, ensuring accurate simulations, embedding domain sizes as small as possible for modeling of convection and conduction heat. These such models provide powerful platforms for studying dependence of temperature distribution, energy storage, and performance of such ponds over time under insolation conditions due to the various possible tube geometrical and orientations.

Mesh Generation and Grid Independence

For more accurate CFD simulations, the meshing has been divided between the structured and unstructured meshing according to the complexity of the geometry. In Design 1, meshing with a structured mesh was used since the geometry is simple. This helped with the uniform distribution of elements. In Designs 2 and 3, for the embedded tube case, unstructured meshing was employed in order to capture curved surfaces and complicated flow paths more efficiently. Mesh quality was optimized by putting a lot of refinement near walls of the tubes and pond boundaries in order to resolve velocity as well as temperature gradients accurately. Grid independent tests were then performed where the number of elements was varied

followed by the study on the changes in the temperature and flow predictions. This was carried out so as to keep a good balance between higher solution accuracy and computational cost that verifies that node distribution was smoothly distributed ensuring a smooth transition between both the coarse and fine regions, hence minimizing numerical errors. The final mesh ensured the convergence criterion necessary to perform reliable input for transient simulations and performance evaluation of different solar-pond designs. Figure 3represents CFD Methods and Algorithms for Analysis
Algorithm used for Computational fluid dynamics analysis

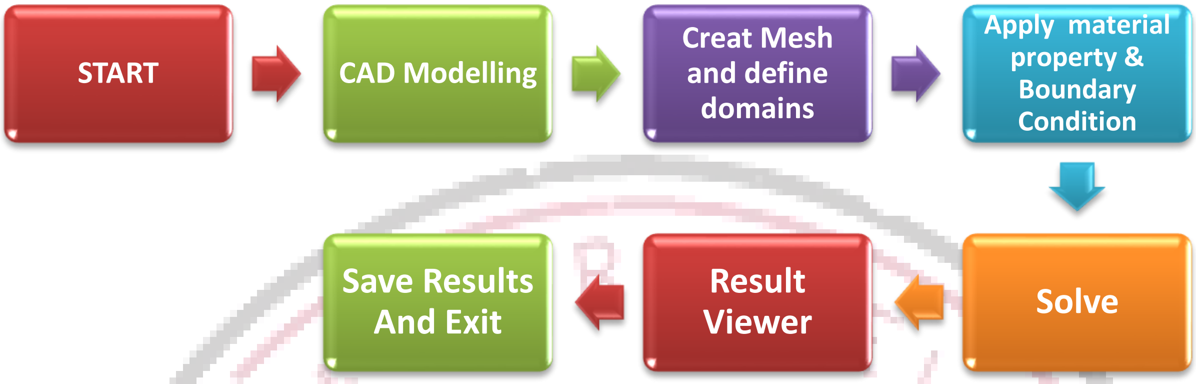

Figure 3: CFD Methods and Algorithms for Analysis

Boundary Conditions and Physical Models

An appropriate physical model and boundary conditions were incorporated into the CFD simulations for realistic behaviors of a pond. Inlet and outlet boundary conditions were specified for heat transfer by embedded tubes, while nonslip conditions were applied to solid boundaries. NaCl-species transport equations were solved for to incorporate with the gradient effects due to salinity, while the energy equation was posed for heat transfer within the pond. The Boussinesq approximation could help model density variation caused by temperature and salinity for simulating natural convection. The transient solver settings have captured the time evolution of temperature and the flow field by solar heating. Historically, neglecting turbulence effects in order to model laminar, stratified flow conditions would be reasonable, considering that thermal radiation is neglected as well. Thus, the proposed modeling framework could assure the proper representation of the coupled heat and mass transfer within the different solar pond configurations.

Governing equations

Applied-governing laws were employed in modeling fluid flow and heat transfer of the solar pond employing the CFD model. The Continuity Equations were enforced throughout the domain to account for mass conservation under conditions of incompressible flow. The momentum equations for three dimensions incorporated the effect of buoyancy-induced convection and viscous forces in the pond. The Boussinesq approximation was applied as a way to model density variations over temperature and salinity gradients. The element of the energy equation linked transient heat transfer-conduction and convective transport. Designs with tubes embedded modeled the convective heat transfer between the fluid and the tube surfaces. The transport equations captured species momentum NaCl to sustain the expected salinity gradient and hence pond stratification. These equations, solved in tandem, modeled the complex thermal and hydrodynamic behavior, thus the analyzing temperature variation, heat storage efficiency, and comparative performance among the three different solar pond designs.

Thermophysical Properties of Heat Transfer Fluids

Heat transfer fluids considered here are water–NaCl solution and water–Al_2O_3 nanofluid. The water–NaCl solution was taken to represent the conventional stratified medium in solar ponds, having varying density and thermal conductivity due to salinity and temperature. The nano-sized aluminum fluoride doped water enhances the thermal transport due to the suspended nanoparticles, resulting in improved heat storage and transfer rates. Temperature-dependent properties such as specific heat, viscosity, and thermal diffusivity were incorporated in the CFD model for reliable prediction. Based on the studies in literatures, the volume fraction of nanofluids and the particle size were chosen to enhance the thermo-fluid behavior within the solar pond without causing huge sedimentation or making a drastic difference with the viscosity of working fluid. The inclusion of these thermo-physical properties has a great potential for performing realistic simulations on the energy storage and extraction processes' quality. This gives a better platform for comparing the performances of working fluids within various solar pond configurations. Observations were made in the transient simulations on the effect of fluid properties on convective stability and heat transfer.

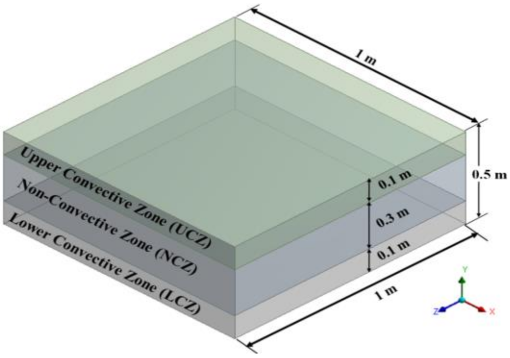

Figure 4: CAD geometry of solar pond for design-1

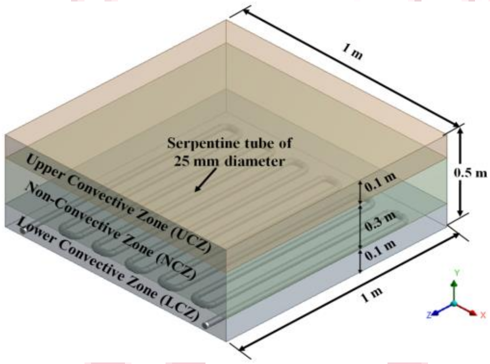

Figure 5: CAD geometry of solar pond for design-2

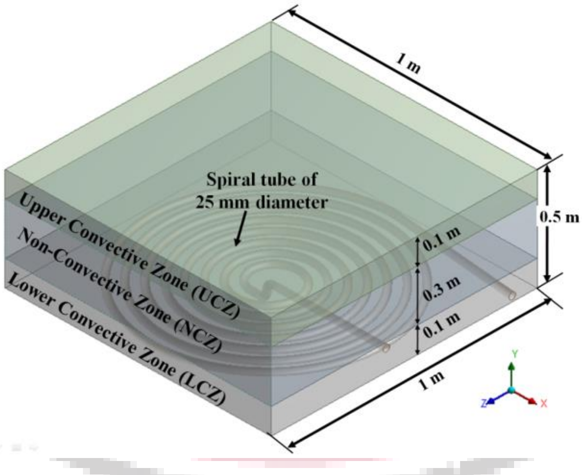

Figure 6: CAD geometry of solar pond for design-3

Post-Processing and Performance Evaluation

Post-processing involved various analyses for temperature distribution, heat storage, and thermal efficiency across all designs of the solar pond. The presentation of contour plots highlighted circling phenomena in Design-1 and improved heat transfer in Designs 2 and 3, caused by the insertion of tubes. The energy storage efficiency was determined by integrating the thermal energy within the pond over the simulation period. A comparative study was carried out to study the influence of tube geometry on heat extraction and pond thermal retention. Parameters like maximum temperature, bottom-layer warming, and heat loss to surroundings were quantitatively measured. In addition to the velocity fields, convection patterns were analyzed so as to establish flow behavior and the potential of thermal mixing. From this assessment, it was proposed that the optimal design would favor the use of serpentine and helical coils to give the best thermal performance coupled with stratification.

Validation of Numerical Model

A numerical CFD model was validated with published experimental and numerical studies to make sure of its reliability. The temperature profiles and energy storage predictions were disseminated and benchmarked by solar pond data, thus capturing some important phenomena such as stratification and heat transfer behavior in the model. Mesh independence and time-convergence tests were conducted based on results that do not discover many differences at further refinement. Moreover, the salinity distribution and convective patterns corresponded with theoretical expectations, ensuring further model validity. When discrepancies were detected, adjustments to the model parameters were done to better verify the generated results. This validation certifies that the simulation framework is not only effective for the prediction of thermal performance in all three solar pond designs but could also provide credibility when proceeding for comparison or parametric studies. The stern validation process measures the validity of this CFD modeling in the design optimization and performance validation.

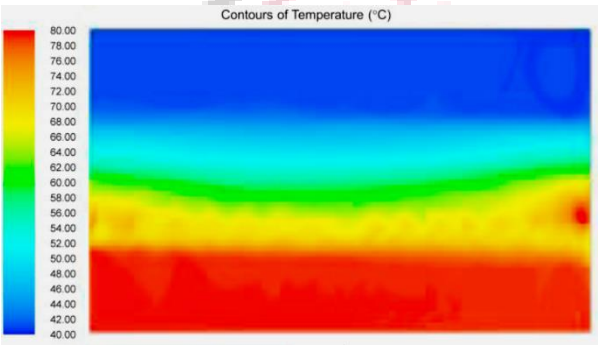

Figure 7: Temperature distribution in solar pond [Khadije El Kadi et al. (2019)]

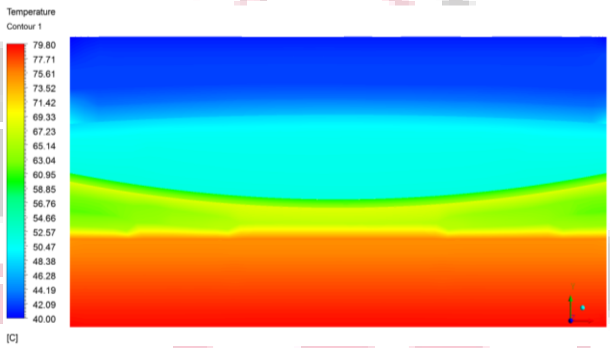

Figure 8: Temperature distribution in solar pond [present work]

Table 2: Comparative results of total elements and temperature distribution between base paper and present work

	Number of Elements	**Maximum Temperature**
Khadije El Kadi et al. (2019)	38400	79.19 C°
Present work	40898	79.80 C°
Percentage variation	6.5%	0.8%

From the contours and graphical diagram, it has been observed that the variation in number of quadrilateral elements is 6.5% while the maximum temperature variation in present work is 0.8% as compared with base paper. All above compared results show very good agreement between present work and published literature, hence the further analysis for different design of solar pond at the same boundary conditions to be done.

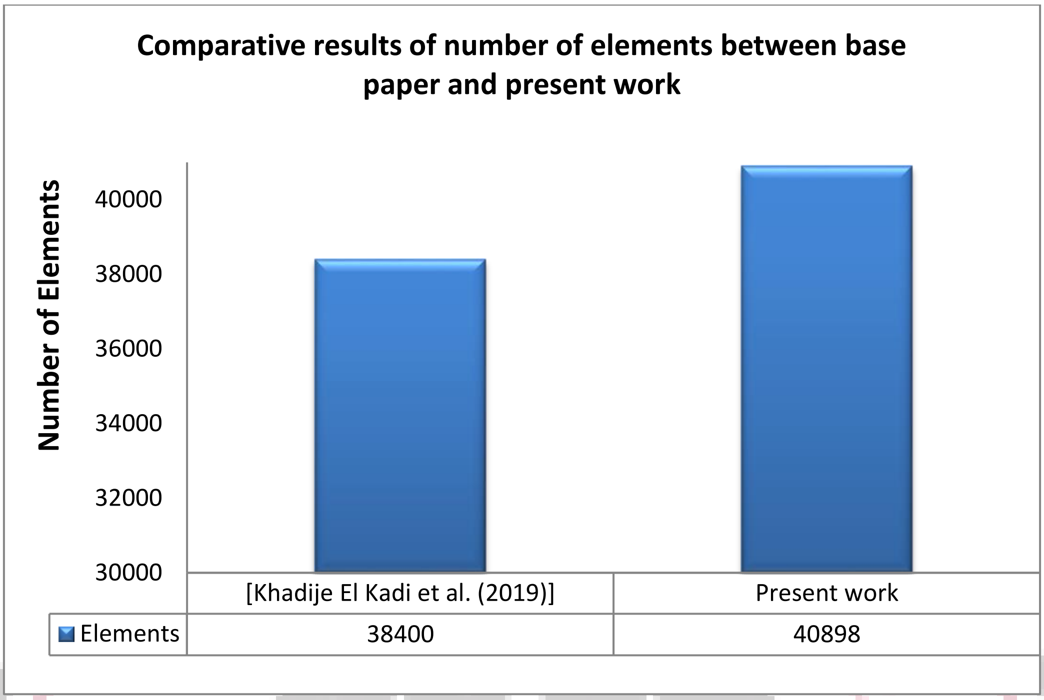

Figure 9: Comparative results of number of elements between base paper and present work

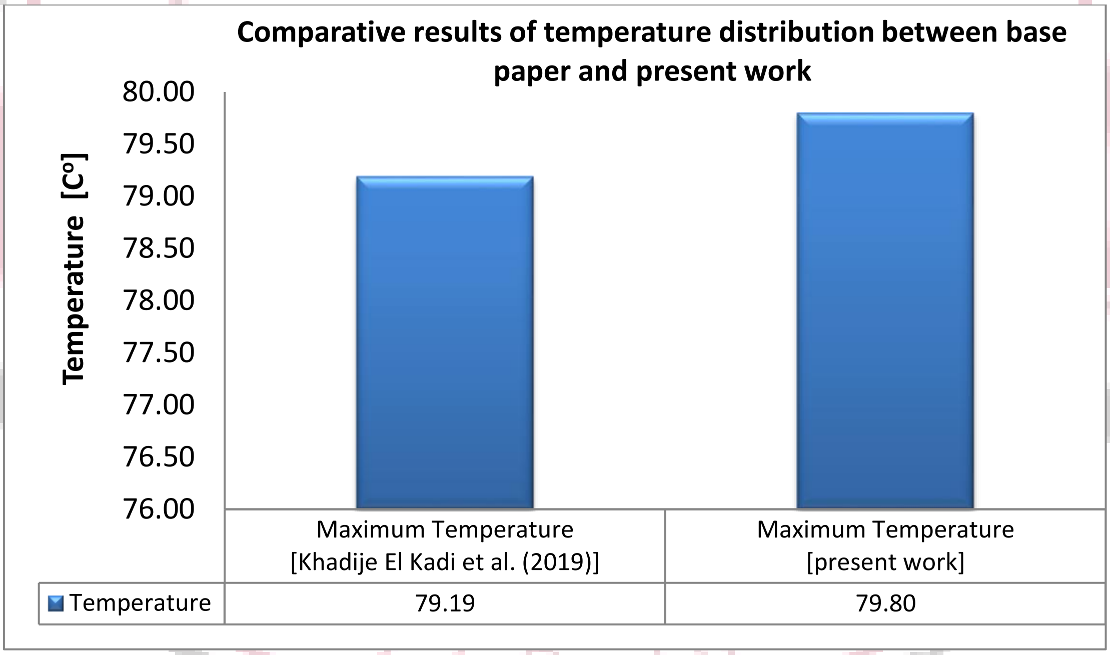

Figure 10: Comparative results of temperature distribution between base paper and present work

V. RESULT AND DISCUSSION

Various numerical models were considered and a comparative analysis made for different solar pond design exploits using mathematical modeling and computational fluid dynamics (CFD). The major objective was to extract improved thermal storage efficacy from solar ponds. In order to fulfill this objective, three different three-dimensional CFD models were made(i) solar pond without any pipes, (ii) one with a serpentine tube configuration, and (iii) another with a spiral tube so as to evaluate and compare the thermal storage performance of all configurations. Now this chapter discusses the findings of the mathematical analyses and the CFD results, discussing the transitory behavior and storage capabilities of solar pond materials.

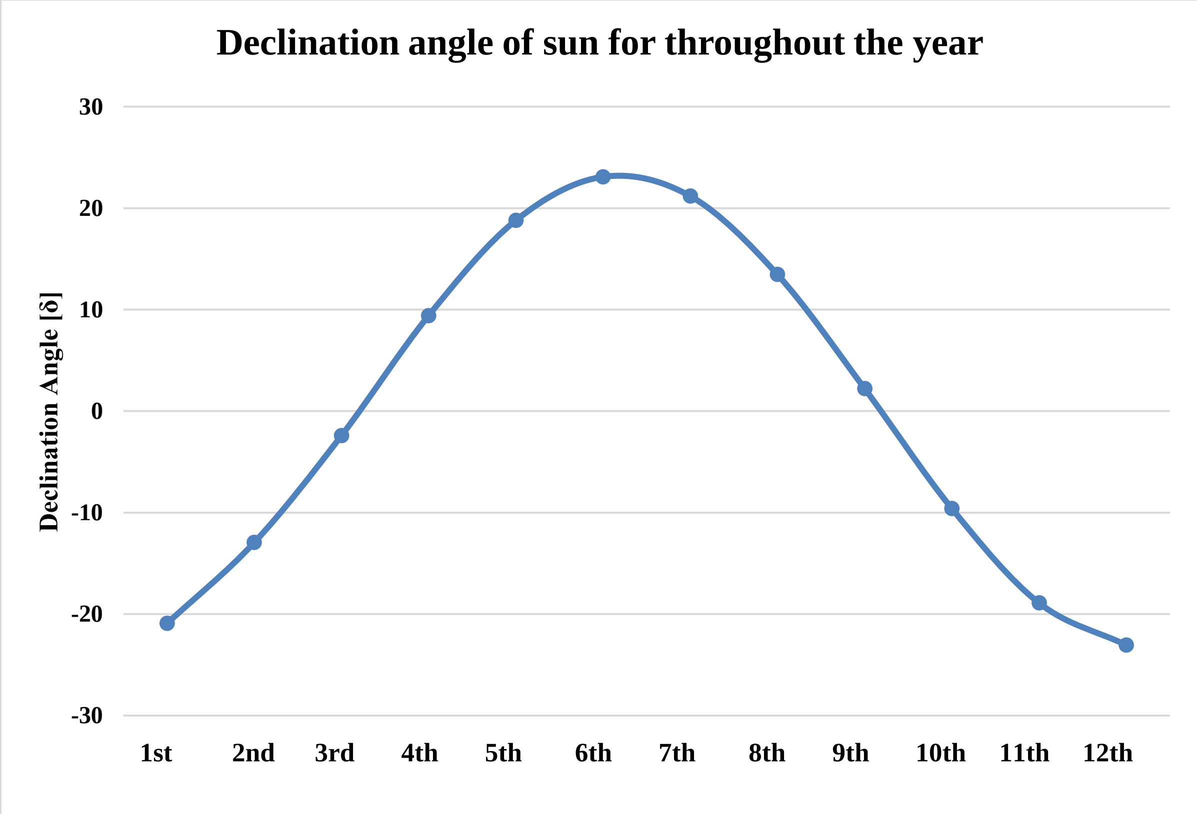

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Figure 11: Calculated Declination angle of sun for throughout the yea

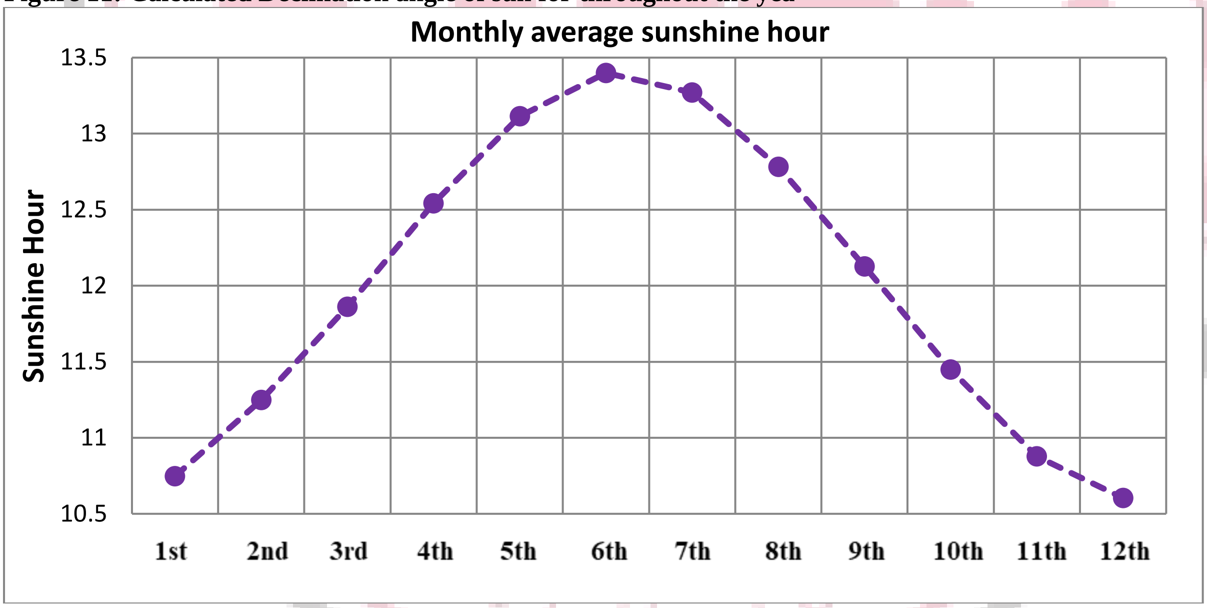

Figure 12: Monthly average sunshine hour

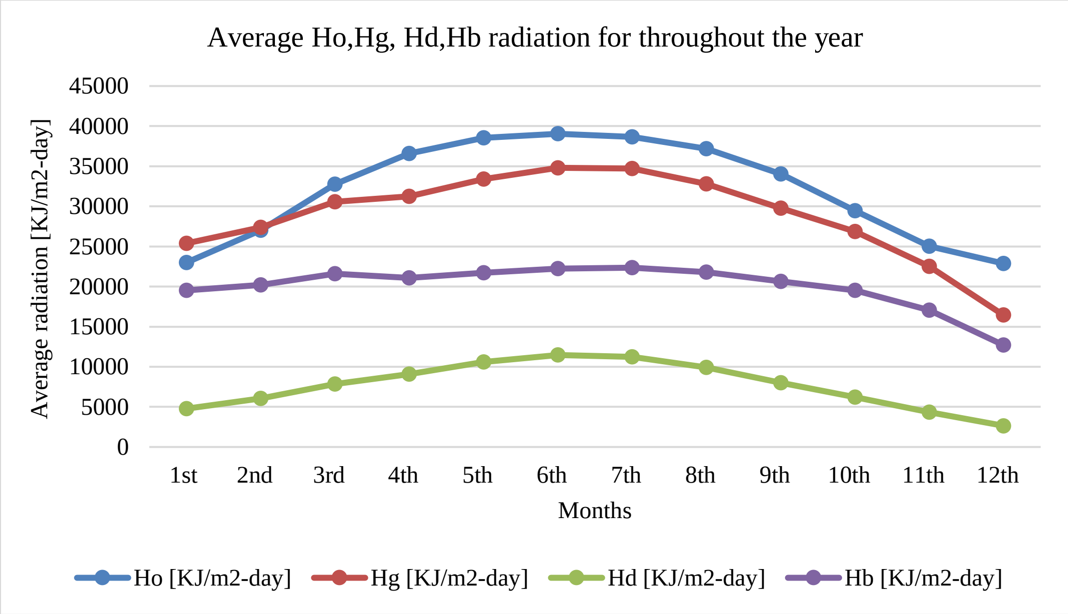

Figure 13: Average Ho,Hg, Hd,Hb radiation for throughout the year

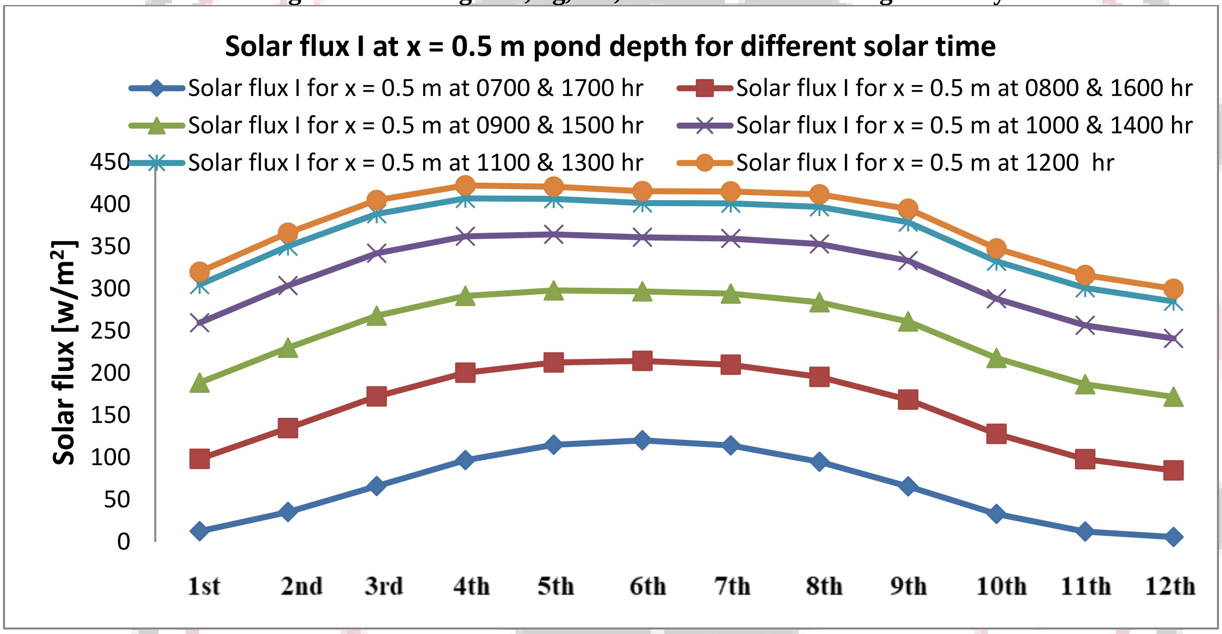

Figure 14: Solar flux I at x = 0.5 m pond depth for different solar time

Table 3: Comparative results of temperature distribution on different layer of solar pond for all designs

Design	Temperature for water with NaCl [C°]	Temperature for water with Al_2O_3 [C°]
Solar pond without tube	80.91	83
Solar pond with serpentine tube	83.16	85.61
Solar pond with spiral tube	92.26	94.75

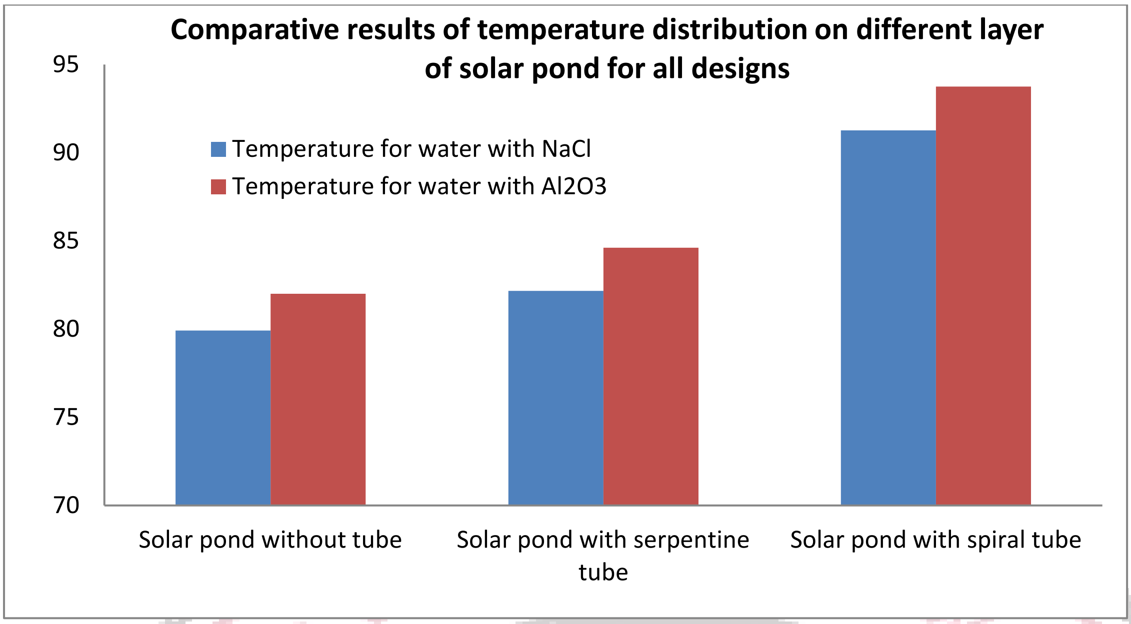

Figure 15: Comparative results of temperature distribution on different layer of solar pond for all designs

Table 4: Comparative results of rate of useful heat extraction on different designs of solar pond

Design	**Rate of useful heat extraction for water with NaCl [W/m^2]**	**Rate of useful heat extraction for water with Al_2O_3 [W/m^2]**
Solar pond configuration without tubing	119.9107	116.525
Solar pond incorporating a serpentine tube	116.2658	112.2969
Solar pond featuring a spiral tube	101.5242	97.4905

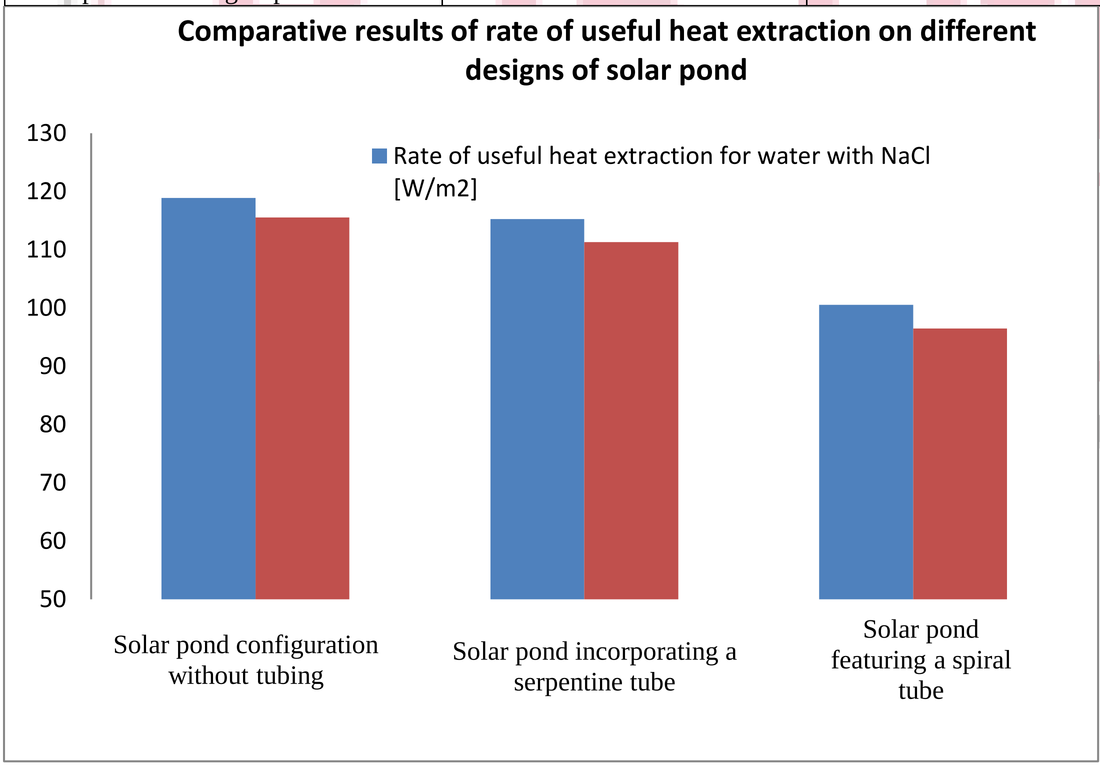

Figure 16: Comparative results of rate of useful heat extraction on different designs of solar pond

Table 5:Comparative results of overall thermal efficiency on different designs of solar pond

Design	**Overall thermal efficiency for water with NaCl [%]**	**Overall thermal efficiency for water with Al_2O_3 [%]**
Solar pond configuration without tubing	18.22	18.87
Solar pond incorporating a serpentine tube	18.92	19.69
Solar pond featuring a spiral tube	21.78	22.56

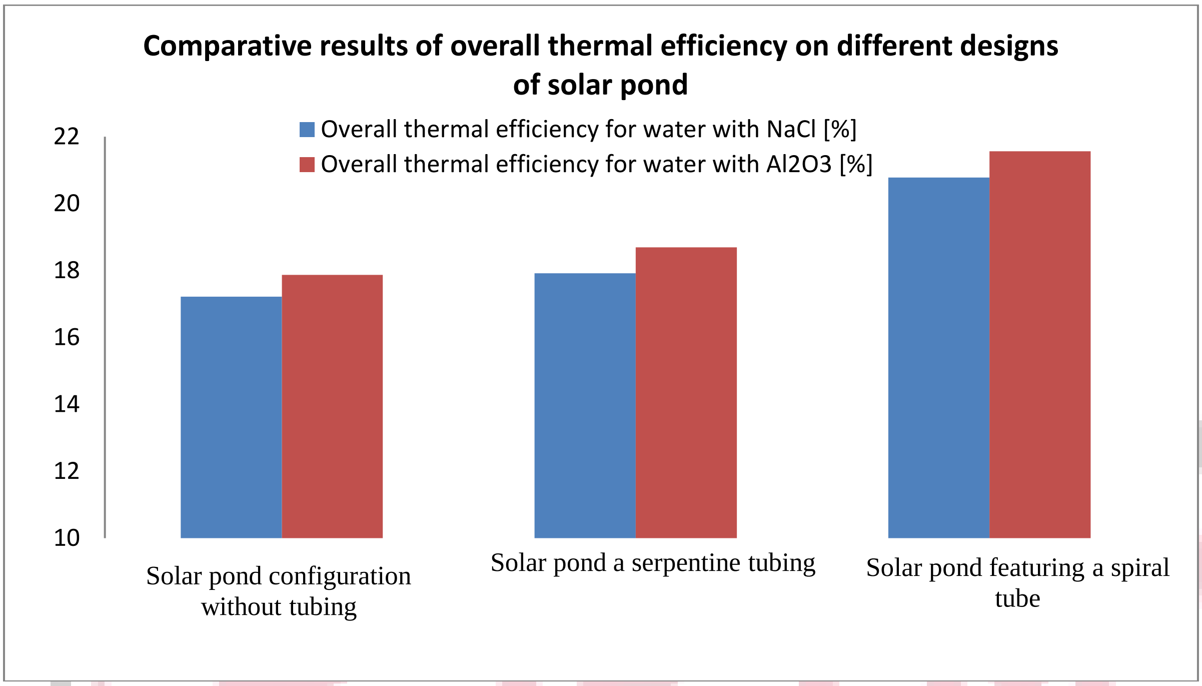

Figure 17: Comparative results of overall thermal efficiency on different designs of solar pond

VI. CONCLUSION AND FUTURE WORK

The present work is a successful attempt to show that the salinity gradient solar ponds can be made more efficient through the combined action of modeling and CFD-based analysis with consequent results in the improvement of thermal performance. The radiation balance computation brings about much more precise estimations concerning solar radiation incident upon the pond and transmission losses indeed which in turn forms a vital consideration in assessing the performance of the solar pond. CFD judgments lend essential insight into temperature distribution, fluid flow patterns, and the heat storage potential vis-à-vis the three-zone solar pond mechanism. A heat extraction system can significantly improve the thermal efficiency of a solar pond. In terms of test cases included in this analysis, it could be summarized that the helical coil heat exchanger-built solar pond maintained very high temperature and more or less uniform thermal distribution in the lower convection zone compared to the other two designs. In conjunction with the addition of a nanofluid such as Al_2O_3 heat transfer purposes were improved because of its exclusive thermophysical properties. This numerical model was confirmed to have accuracy with slight deviation from lesser temperature predictions when matched against published literature. Future research may focus on longer transient simulations to evaluate seasonal performance variations of solar ponds. The experimental validation of proposed configurations under real climatic conditions would further strengthen the results. It may be worth investigating optimization studies concerning differences in nanofluid concentrations, alternative coil materials, and hybrid renewable integrations. Techno-economic feasibility and environmental impact assessment of such large-scale solar ponds altogether make for a promising direction for further study.

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