Central Tower Solar Receiver Structures: Construction and Performance Comparison"

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Abstract. The purpose of this study is to evaluate the design and thermal performance of various configurations of central tower solar receivers, with an emphasis on spiral tube receivers. Specifically, it addresses the challenges of cost-effectiveness and efficiency within Concentrating Solar Power (CSP) systems. Multiple designs are assessed using a combination of analytical models and computational fluid dynamics (CFD) tools to assess thermal efficiency, heat transfer, and convective losses. Spiral tube receivers demonstrate superior thermal characteristics across various metrics as a result of the grid independence tests. Additionally, we discuss the effects of various mass flow rates on the outlet temperatures of the heat transfer fluid (HTF), in order to improve solar energy capture and conversion by optimizing the receivers.

Keyword-: CSP, heat transfer fluid, CFD analysis, solar recievers.

1 Introduction

Since Concentrating Solar Power (CSP) systems have higher levelized costs of power than solar photovoltaic systems, they have not been as successful commercially. The advantages of hybrid power plants include continuous power generation and hybridization. The cost of storage systems for CSP technologies needs to be reduced and cycle efficiencies must be improved to compete [1]. Instead of using solid particles, high temperatures gas is first obtained using solidified particles in photovoltaic receivers. Solid particles in a solar receiver

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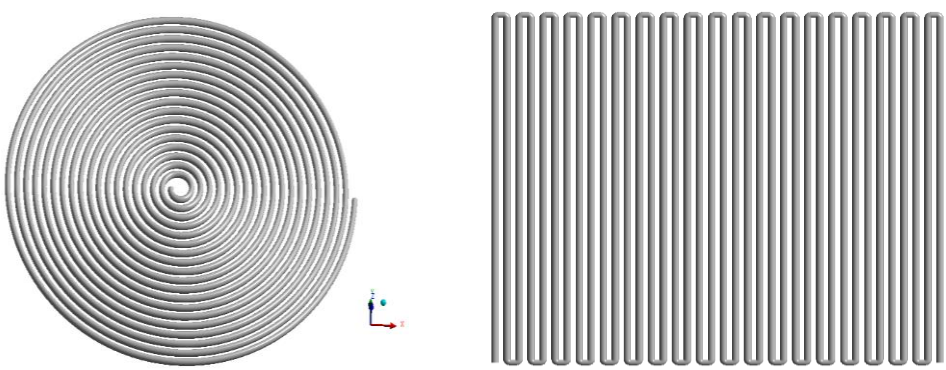
transfer absorbed heat to the incoming gas stream [2]. The heat is transferred via phase-based receivers. Liquid tubular photovoltaic receivers are most often used in CSP tower systems. A large number of research efforts have been conducted to make use of this technology since the 1970s. CSP tower systems currently use only liquid tubular receivers [3,4]. It is critical that solar concentrator photovoltaic (CPV) receivers are efficient when building solar devices and systems. Heat exchangers are installed in some of these receivers, which are composed of layers of solar cell compounds. It is more efficient to convert renewable energy from CPV receivers than from non-concentrating components. It is crucial to comprehend how CPV functions in different environmental settings in order to estimate energy production accurately and increase system efficiency [5].Numerous types of solar receivers were designed to utilize solar energy, these designs and are compared in Table 1. The energy and energy performance of an external spiral tube receiver for a solar parabolic dish concentration under three distinct radiation scenarios is examined in [6]. With an average thermal and energy efficiency of 56.21% and 5.45%, respectively, and a total loss of heat rate of 182 W/Mk, the results point to the possible use of this inexpensive, lightweight receiver in process heating applications. Using Trace Pro optical software, the optical quality of photovoltaic cavity receivers with and without spiral pipes has been mimicked for the inquiry. It looked at how the receivers performed in relation to the reflectivity of the wall within and the outer diameter and pitched of the spherical tubes. The findings demonstrated that the inner wall should not be approximated as the spiral tube's outer surface. The study in [7] finds that higher reflectivity pitches can improve the optic effectiveness of transmitters; the best performance antennas are truncated-cylindrical receivers, with an optically effectiveness of 85.42%. These findings give theoretical advice for receiver optimization and design. The goal of the [8] is to use a photovoltaic dishes concentration system to develop a successful solar energy receiver. A spiral coil's several the convolutions are analyzed thermally and dynamically, and the redesigned absorber is tested through tests. Anodized aluminum and copper are used for reflecting surface and absorbers in the current structure, which also includes five the convolutions of a spiral coil tube absorber. According to the study, the highest absorbers temperature recorded in May was 296°C, while the highest working fluid outlet temperature recorded was 294.2°C. The work presented in [9] uses a thermal model for optical, heat, and exergetic research to contrast two hollow transmitters for a solar dish concentrate. In order to properly simulate and evaluate the spiral absorber model, 13 coil are used for every idea when used with an optic tool. Improvements inefficiency of 1.38% are achieved by positioning the receiver optimally for visual efficiency. Heat effectiveness rises with conical design by 5.63% at 100°C and 40.45% at 200°C, whereas energy use increases by 6.67% at 100°C and 42.06% at 200°C.Utilizing a mathematical framework and ANSYS Fluent software for nine mirrors, the study in [10] evaluates the spiraling receiver's outlet temperature. Accurate CFD results are used to study the recipient's temperature variations and heat transmission properties with increased heat transfer coefficients, the temperature of the fluid was regulated by the amount of heliotropes and mass flow rate. It achieved its highest temperature of 92.4°C at noontime and a mean temperature of 84.4°A during the day.Using a thermal model created in Optis Work and the Engineering Equation Solver, [11] explores an inexpensive solar power system with a spiral absorber and dish reflector. In spite of substantial heat losses, the results indicate a 34% thermal performance. Tests are conducted on the model using different fluid mixes and operational circumstances. According to the study, thermal oil works best at higher temperatures, while water serves as the best fluid for work at lower ones. Air is the ideal option for low temperatures and thermal oil for higher temperatures, according to energetic study .One possible heat-transfer medium for sunlight to gas turbines is high-temperature air. Using a 7-kW Xe-arc lamp array system and 8 K-type thermocouples, which a 15-turn receivers with an optic splitter was built and tested. The radiation energy distribution on the inside sidewalls of a cavity is simulated using the Lambert test technique and a Monte-Carl ray-tracing method. A thorough simulation model that displays outlet temperature variances for down and up flows to 8.0% and 2.5%, respectively, is suggested in [12-15]. The output temperature can rise to 800°C under 300 kW/m2, and the model offers optimization strategies to increase efficiency and decrease heat losses.

Table 1: Comparison of different solar receiver designs by numerous researchers and their performance

Study	Method/Technology Used	Key Findings and Efficiency	Temperature Achievements	Optimization/Improvement Strategies	Potential Applications/Theoretical Advice
[16]	External spiral tube receiver with TracePro software	Avg. thermal efficiency: 56.21%, Avg. energy efficiency: 5.45%, Total heat loss: 182 W/Mk	-	-	Suitable for process heating; Importance of accurate surface modeling
[17]	Optical quality of PV cavity receivers with/without spiral pipes	Best optical effectiveness: 85.42% with high reflectivity pitches	-	High reflectivity pitches improve optical effectiveness	Optimization of receiver design for enhanced optical effectiveness
[18]	Photovoltaic dishes with spiral coil absorber, anodized aluminum, and copper	Highest absorber temp: 296°C, Highest fluid outlet temp: 294.2°C	Absorber: 296°C, Fluid outlet: 294.2°C	Analysis of spiral coil convolutions	Development of effective solar energy receivers
[19]	Thermal model for optical, heat, and exergetic research on hollow transmitters	Improvement in efficiency by 1.38%, Heat effectiveness increase by 5.63%-40.45%	-	Optimal positioning for visual efficiency, Conical design improves heat effectiveness	Comparing hollow transmitters for solar dish concentrate
[20]	CFD analysis with ANSYS Fluent for	Highest temperature	Highest: 92.4°C,	Adjustments in heliotropes and mass flow rate	Thermal performance and

	spiraling receiver	achieved: 92.4°C, Mean temperature: 84.4°C	Mean: 84.4°C		heat transmission analysis
[21]	Thermal model with Optis Work and Engineering Equation Solver for spiral absorber	Thermal performance: 34%, Best fluid for high/low temp: Thermal oil/Water	-	Testing with different fluid mixes and operational conditions	Inexpensive solar power system design
[22]	Simulation with Monte-Carl ray-tracing, Lambert test for a 15-turn receiver with optic splitter	Outlet temperature variance down/up flow to 8.0%/2.5 %, Potential for 800°C under 300 kW/m2	Up to 800°C under 300 kW/m2	Optimization strategies to increase efficiency and reduce heat losses	Heat-transfer medium for sunlight to gas turbines

2 CAD Modelling



(a) (b)

Fig.1: Solar receivers (a) Spiral shaped tube; (b) Vertical-tube shaped

The precision and accuracy of computational simulations rely upon grid independence, which shows that changes in grid density have no effect on outcomes and may thus ignore truncation mistakes. The accuracy of the results and truncation mistakes are both strongly impacted by the degree of grid independence [24-27. This problem may be addressed by performing grid independence tests, although using very thick grids might result in needless use of computer resources [28]. In real-world applications, the technique often entails comparing the results from neighboring resolutions and gradually increasing grid resolution by a given ratio. Grid independence promotes economical use of processing resources while producing precise and logical conclusions when these evaluations converge regarding the same outcomes.

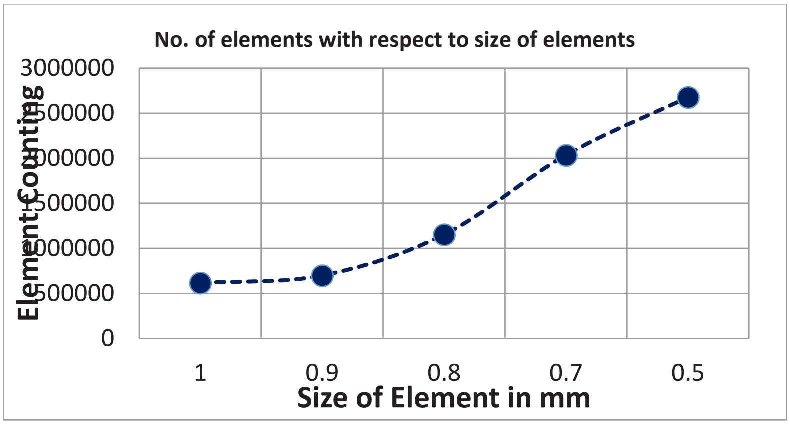


Fig. 2: Element Count Variation with Size in Grid Independence Testing

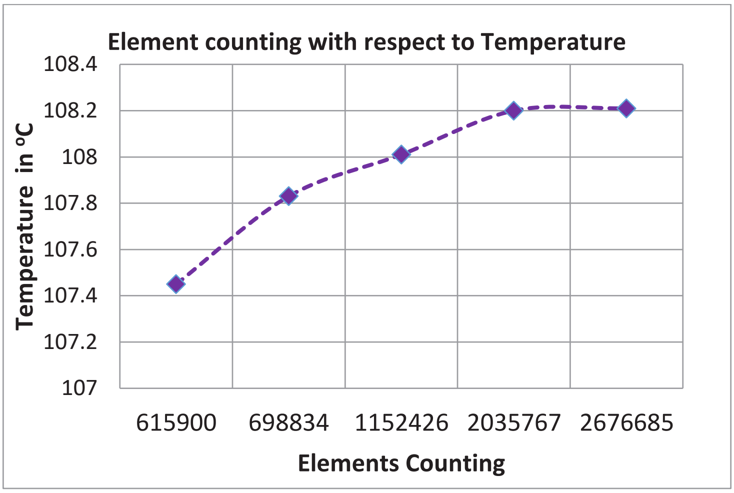


Fig. 3: Temperature Analysis via Grid Independence Verification

In the Fig. 3: Temperature Analysis via Grid Independence Verificationcurrent research, the performance of a central tower solar receiver was assessed through grid independence tests [29], focusing on temperature distribution at a flow rate of 0.1 liters per minute (LPM) for different sizes of mesh elements, as illustrated in the accompanying figures. The results revealed that an element size of 0.7 mm produced the best results when compared to the other sizes evaluated**.**

3 Result Obtained and Discussion

The primary aim of this study is to create a design for a central tower solar receiver plant that features a central receiver with both the inlet and outlet positioned at the bottom, a vertical solar central receiver with the inlet at the bottom and the outlet at the top, and a spiral receiver [30]. This research introduces an analytical model to calculate the outlet temperature for the aforementioned designs of the central receiver. To ascertain the outlet temperature of the heat transfer fluid (HTF) across various mass flow rates—specifically at 0.1 LPM, 0.2 LPM, 0.3 LPM, 0.4 LPM, 0.5 LPM, and 0.6 LPM—with an inlet temperature of the HTF set at 299K, a detailed thermal analysis will be performed. Thermal behavior of the HTF is modeled using thermodynamic principles and heat transfer equations. For effective heat transfer, the specific heat capacity of the HTF, the thermal properties of the materials involved, and the mechanisms involved will be considered [31-34]**.**

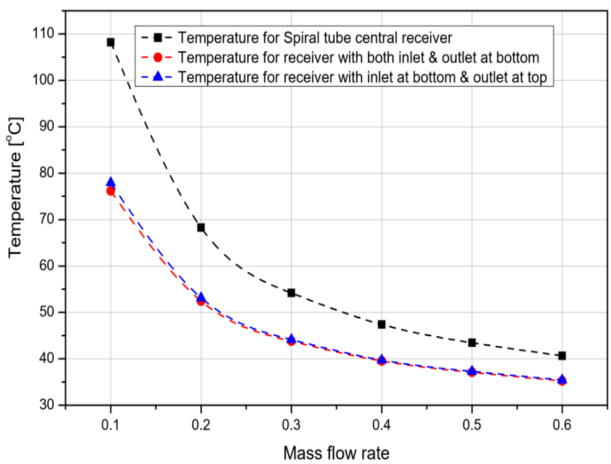


Fig. 4: Various solar receiver designs are compared for temperature variations

The graph provided in Fig. 4 shows a comparative analysis of temperatures at for three different types of solar central receivers as a function of the mass flow rate [35]. It illustrates that the outlet temperature decreases with increasing mass flow rate for all designs, with the spiral tube central receiver showing the highest temperatures across all flow rates, followed by the receiver with both inlet and outlet at the bottom, and the receiver with inlet at the bottom and outlet at the top exhibiting the lowest temperatures [36].

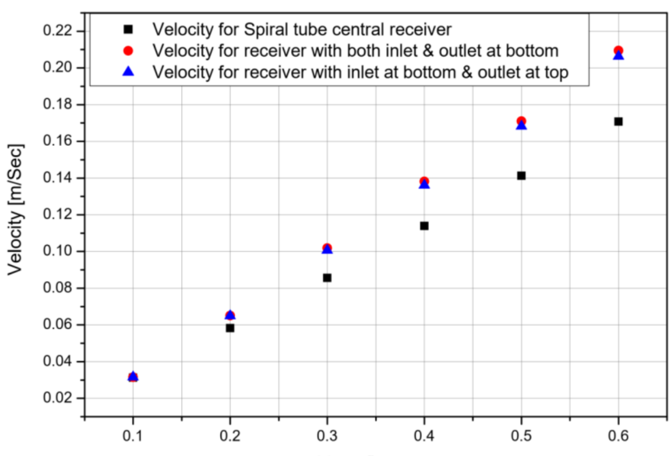


Fig. 5: Comparison of velocity variations for different designs of solar receivers

The graph provided in Fig. 5 displays the variation in velocity profiles for three solar receiver designs at different mass flow rates, which ranges from 0.1 – 0.6 (LPM). As there is increase in mass flow rate the increase in velocity of the heat transfer fluid is observed for all designs [37]. Among the designs, the spiral tube central receiver consistently demonstrates the highest fluid velocity, followed by the receiver with both inlet & outlet at the bottom, while the receiver with the inlet at the bottom and outlet at the top has the lowest velocities at corresponding flow rates.

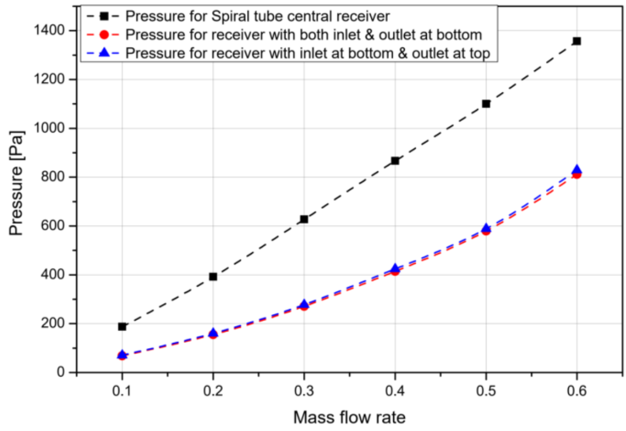


Fig. 6: Comparison of variations in pressure for different designs of solar receivers

The comparative analysis of the CFD results for different central tower receiver designs indicates that at 0.1 LPM, the spiral tube central receiver achieves the highest temperature, according to Fig. 4, which is 41.06% more than that of the vertical solar central receiver with both inlet and outlet at the bottom and 37.64% more than the vertical tube central receiver with inlet at the bottom and outlet at the top. As shown in Fig.5, variation in velocity, at 0.6 LPM, the spiral tube central receiver records a maximum of 0.1607 m/sec, while the vertical solar central receiver with both inlet and outlet at the bottom reaches 0.2186 m/sec, and the vertical tube central receiver with inlet at the bottom and outlet at the top reaches 0.2043 m/sec. In terms of pressure as depicted in Fig. 6, the spiral tube central receiver exhibits a peak of 1346 Pa, compared to 810.50 Pa for the vertical solar central receiver with both inlet and outlet at the bottom and 827.30 Pa for the vertical tube central receiver with the inlet at the bottom and outlet at the top, all measured at 0.6 LPM.

The analysis of Fig. 7, which presents a comparison of the convective heat loss coefficients for various designs of central tower receivers, reveals that the spiral tube central receiver has a convective heat loss of 6.25 W/m²K. This value is approximately 2.5% lower than that of the vertical tube central receiver with the inlet at the bottom and outlet at the top, and 2.6% lower than the vertical solar central receiver with both the inlet and outlet at the bottom. Moreover, it is significantly 36.74% higher when compared to outlet at top.

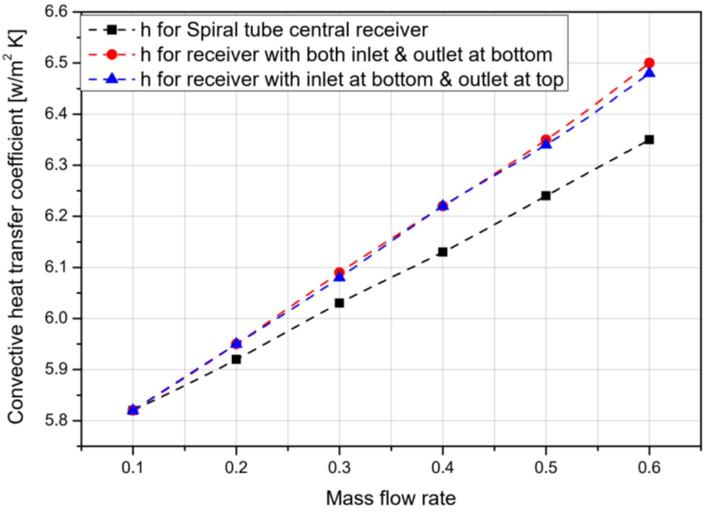


Fig. 7: Comparison of convective heat loss coefficient for different designs of solar receivers

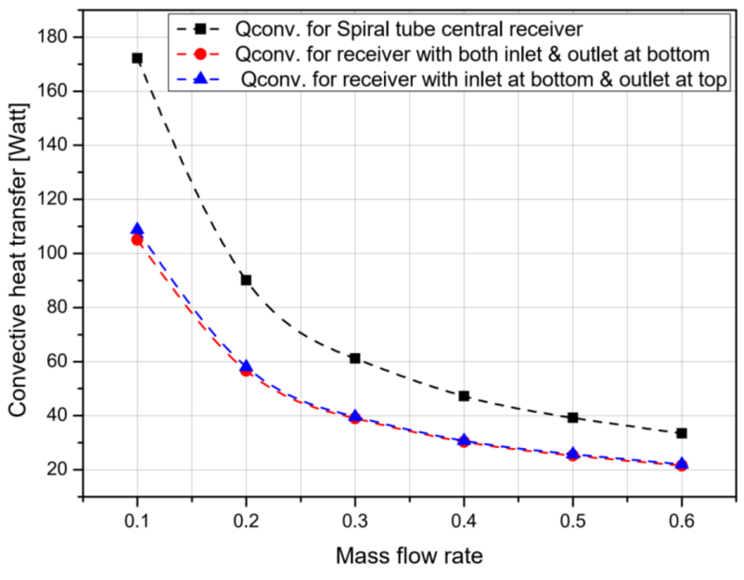


Fig. 8: Comparison of convective heat transfer for different designs of solar receivers

From the comparative data in Fig. 8 on convection heat transfer across different central tower receiver designs, it's noted that the spiral tube central receiver exhibits a 64.96% greater convective heat transfer rate compared to the vertical solar central receiver with both inlet and outlet at the bottom. Additionally, it has a 57.56% higher rate than the vertical tube central receiver with the inlet at the bottom and the outlet at the top.

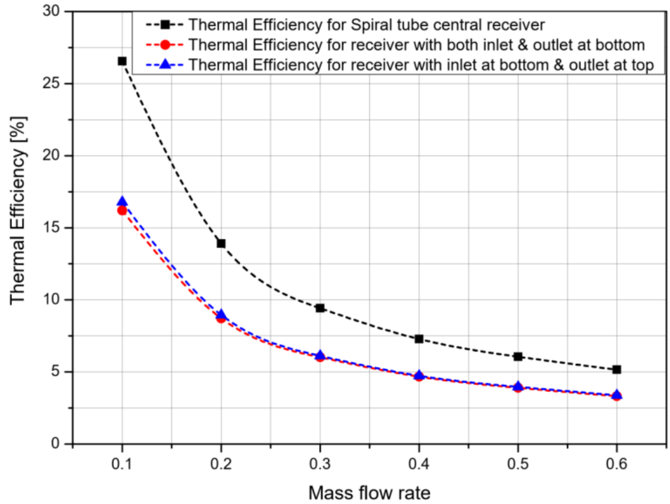


Fig. 9: Comparison of thermal efficiency for different designs of solar receivers

The comparative analysis in Fig. 10 reveals that, concerning all the central tower receiver designs examined, the spiral tube central receiver demonstrates a 62.69% higher thermal efficiency compared to the vertical solar central receiver, which has both inlet and outlet at the bottom. Furthermore, its thermal efficiency surpasses that of the vertical tube central receiver, which features an inlet at the bottom and an outlet at the upper end, by 56.72%.

4 Conclusion

The comprehensive analysis conducted in this study concludes that the spiral tube central receiver outperforms its counterparts in terms of thermal efficiency, temperature maintenance, and convective heat transfer rates. This receiver design, with its unique structural attributes, shows a 62.69% higher thermal efficiency compared to the vertical solar central receiver with both inlet and outlet at the bottom, and 56.72% higher than the vertical tube central receiver with inlet at the bottom and outlet at the upper end. These results underscore the spiral tube receiver's viability for commercial application within CSP systems, providing a path towards more efficient and cost-effective solar power generation. Future work should focus on addressing the identified convective heat loss challenges and exploring scalable storage solutions to bolster CSP competitiveness in the renewable energy market.

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