# Optimization of Parabolic Trough Design for Enhanced Efficiency in Solar Thermal Systems

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**Abstract.** In order to increase the efficiency of Parabolic Trough Collectors (PTCs) in solar thermal applications, this study proposes an optimal design for these devices. Non-uniform heat distribution, which lowers thermal efficiency and results in material stress, is a major drawback of traditional PTC systems. In order to improve solar flux concentration and uniformity, a novel arrangement that incorporates a plano-convex lens above the receiving tube has been devised. Heat flow distribution and system behavior under different environmental circumstances were analyzed using SolTrace optical modeling and computational fluid dynamics (CFD) simulations. A steady-state analysis of turbulent, incompressible flow with mixed convection was part of the research methodology. Furthermore, a discrete ordinate technique was used to describe the thermal radiation between the absorber tube and the glass envelope. An accurate evaluation of improvements in solar flux concentration brought about by lens integration was made possible using SolTrace simulations. Wind load testing guaranteed operational stability in harsh circumstances, while structural analysis verified that the reflecting sheets deformed minimal under loading. According to the results, the plano-convex lens raises the concentration of solar flux, which increases structural stability and thermal efficiency. A more consistent temperature distribution along the receiver tube was shown by integrating SolTrace for optical validation. The system's long-term operational viability was validated by structural simulations, which confirmed its resilience in harsh environmental circumstances. By putting out an affordable strategy for enhancing the longevity and efficiency of PTC systems, this study advances renewable energy and speeds up the shift to sustainable energy sources.

**Keywords:** Parabolic Trough Collector, Solar Thermal Systems, SolTrace, Heat Flux Distribution,

## 1 Introduction

Solar thermal technology has become a competitive alternative to traditional fossil fuel-based power generation as the world moves toward sustainable energy sources [1]. Because of their exceptional effectiveness in absorbing and transforming solar radiation into thermal energy,

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Parabolic Trough Collectors (PTCs) have become well-known among other solar thermal technologies [2,3]. These systems are used in home water heating, industrial heating, and power generating. Their longevity and performance are, however, impacted by important issues like as uneven heat distribution, thermal and optical losses, and material deterioration [4,5].

Optimizing PTC design and increasing its thermal efficiency is the main goal of this study. This project investigates new energy gathering methods, advanced design, and improved heat distribution. In addition to increasing efficiency, the suggested enhancements seek to lower energy costs, increasing the commercial viability of solar thermal applications [6,7].

By tackling these issues, the research's conclusions support global sustainability initiatives by encouraging cleaner energy sources and lowering reliance on fossil fuels [8].

## 2 Objectives

### 2.1 Challenges in PTC Systems

#### *2.2.1 Non-Uniform Heat Distribution*

Uneven heat flux on the receiver tube leads to thermal inefficiencies and material stress, reducing system lifespan and performance [9].

#### *2.2.2 Solar Flux Concentration Optimization*

Optical scattering and reflection losses hinder uniform solar flux concentration. A plano-convex lens above the receiver tube is introduced to enhance light focusing and improve heat distribution [10].

#### 2.2.3 Structural Integrity and Environmental Resilience

PTC systems must endure high wind loads, extreme temperatures, and structural deformations. Ensuring minimal reflector deformation and maintaining optical alignment are crucial for operational stability [11].

### 2.3 Approach to the Problem

#### *2.3.1 Plano-Convex Lens Integration*

The study proposes integrating a plano-convex lens above the receiver tube to optimize heat flux distribution and minimize thermal stress, leading to uniform temperature profiles [12].

#### *2.3.2 CFD and SolTrace Simulations*

Advanced Computational Fluid Dynamics (CFD) simulations analyze heat transfer under turbulent, incompressible flow conditions. SolTrace optical modeling evaluates the effectiveness of solar flux concentration improvements. Méthodology is shown in Fig.1.

#### *2.3.3 Structural Optimization*

Reflector sheets undergo static and dynamic loading analyses to ensure minimal deformation. High-speed wind load simulations validate the robustness of the structure.

## 2.4 Key Findings and Impact

### *2.4.1Enhanced Thermal Efficiency*

The integration of a plano-convex lens leads to more uniform heat distribution, improving system performance [13].

### *2.4.2Improved Structural Reliability*

Optimized design ensures long-term durability under operational stresses.

### *2.4.3Economic Viability*

The proposed modifications offer a cost-effective approach to increasing solar thermal efficiency [14].

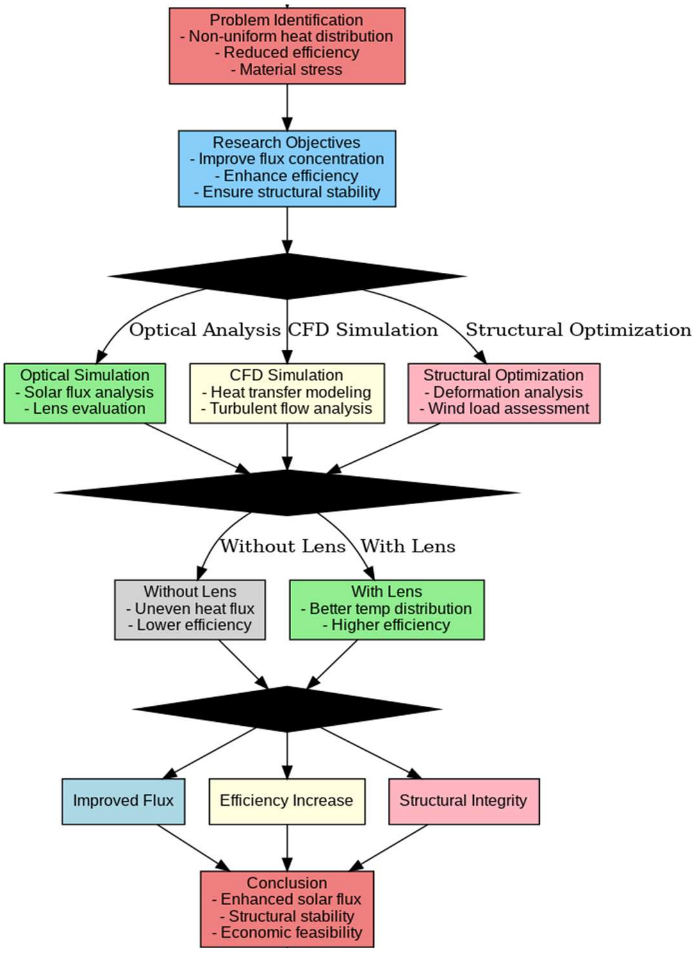


**Fig.1**. Methods

## 3 Optical Method

The optical modeling process aims to evaluate power concentration on the absorber tube and heat flux variations under different optical configurations. Simulation Setup: Conducted using SolTrace for Delhi (28.7041°N, 77.1025°E) at a Direct Normal Irradiance (DNI) of 1000 W/m².
Sun Model: Pillbox distribution with a half-width of 4.65 milliradians.
Material Selection: High-reflectivity aluminum for reflectors and black chromium-coated stainless steel for the absorber tube [15].
Material Properties
Reflector Material: High-reflectivity aluminum, chosen for efficient redirection of solar radiation onto the receiver.
Absorber Material: Stainless steel coated with black chromium, enclosed in a protective glass envelope to minimize thermal losses and ensure durability under high temperatures.
Optical Performance Analysis
Without Plano-Convex Lens: Solar rays are not concentrated at a single focal point, leading to lower heat flux on the receiver tube [16].
With Plano-Convex Lens: Light is focused precisely on the receiver tube, leading to higher heat flux concentration and increased thermal efficiency. PTC optical component properties is shownin Table 1.

Governing equation in oltrace Optical efficiency

$$\eta_{opt}(\theta) = K(\theta) \times \eta_{opt-max}$$

Incidence angle

$$K(\theta) = cos(\theta) - \frac{f}{L}(1 + \frac{W^2}{48f^2}) \times sin(\theta)$$

**Table 1.** PTC Optical Components Properties

| | Absorptivity | Reflectivity | Transmissivity |
|---|---|---|---|
| Receiver tube | 0.95 | 0 | 0 |
| Glass envelope | 0.01 | 0.01 | 0.965 |
| Reflector | 0 | 0.95 | 0.05 |

Assumptions for CFD Modeling: In this study, Syltherm 800 has been chosen as the working fluid due to its superior specific heat capacity and thermal conductivity, making it an efficient medium for heat absorption and transfer. Additionally, it is cost-effective and safe for a range of thermal applications.
Steady-State Assumption: The computational analysis is conducted under steady-state conditions, meaning that variables such as temperature, velocity, and heat flux remain constant over time. This assumption is justified for solar thermal systems, where operational conditions tend to stabilize after an initial transient phase. The steady-state approach simplifies simulations while providing accurate insights into system behavior. Turbulent Flow Consideration: The flow inside the receiver tube is treated as fully turbulent due to the high Reynolds number, a standard characteristic of PTC receiver designs. Turbulence

enhances heat transfer by promoting increased mixing and energy dissipation, making this assumption essential for obtaining reliable simulation results.

Incompressible Fluid Assumption: Syltherm 800 is assumed to be incompressible, implying that density variations due to pressure and temperature changes are negligible. This assumption is valid as the temperature gradients within the receiver tube are not sufficiently large to induce significant changes in fluid density.

## 4 Mixed Convection Modelling

Heat transfer inside the receiver tube is governed by mixed convection, incorporating both forced convection (due to fluid motion) and natural convection (resulting from temperature gradients). Given that the lower half of the receiver tube receives intensified solar flux, while the upper portion experiences comparatively lower heat inputs, a mixed convection approach is necessary to accurately represent the system's thermal behavior as shown in Figs 2 to 9.

Vacuum Insulation Effect -To minimize convective heat losses, the receiver tube is enclosed within a glass envelope under vacuum. This insulating barrier prevents heat dissipation to the surroundings and ensures that heat transfer within the system occurs predominantly through radiation and conduction. Heat flux for both cases is shown in Table 2.

The governing equations for the CFD simulation include:

$\partial u/\partial x = \partial v/\partial x = \partial w/\partial x = \partial k/\partial x = \partial \epsilon/\partial x = \partial p/\partial x = \partial T/\partial x = 0$

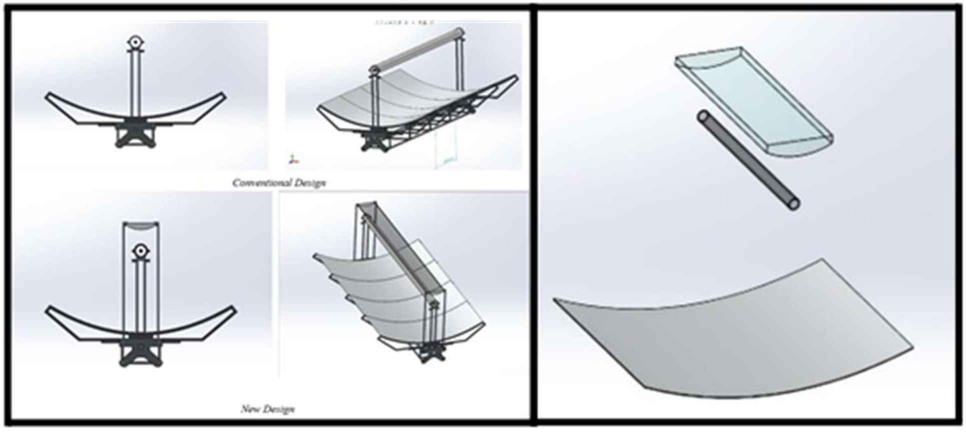
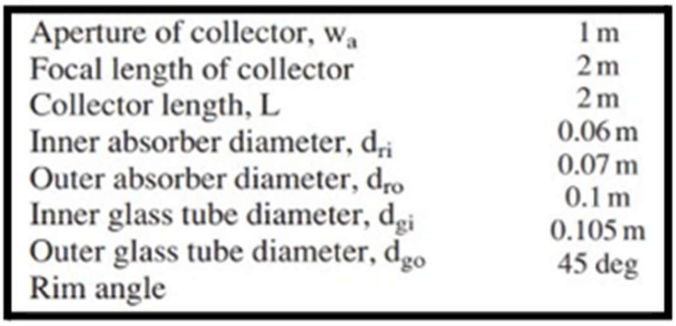


**Fig. 2:** Plano-Convex Lens



| | |
|---|---|
| Aperture of collector, $w_a$ | 1 m |
| Focal length of collector | 2 m |
| Collector length, L | 2 m |
| Inner absorber diameter, $d_{ri}$ | 0.06 m |
| Outer absorber diameter, $d_{ro}$ | 0.07 m |
| Inner glass tube diameter, $d_{gi}$ | 0.1 m |
| Outer glass tube diameter, $d_{go}$ | 0.105 m |
| Rim angle | 45 deg |

**Fig.3**. *Optical component properties*

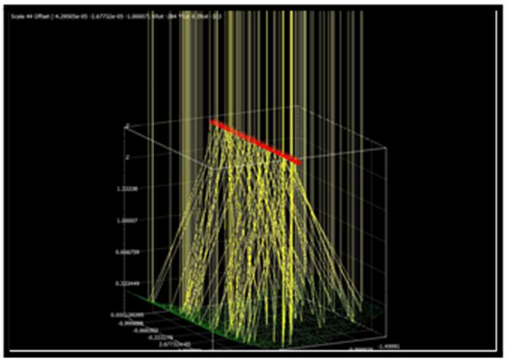


**Fig.4.** Ray Tracing without convex lens in SOLTRACE

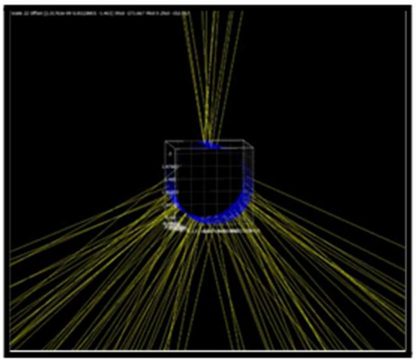


**Fig. 5.** Ray Tracing with convex lens in SOLTRACE

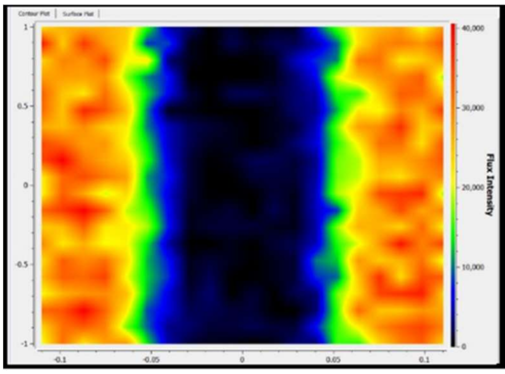


**Fig.**6.flux distribution without integration of lens

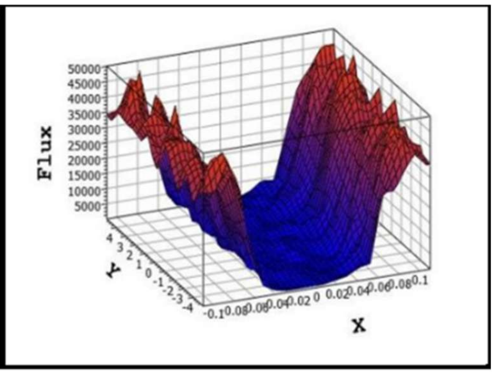


**Fig.7**. Surface plot of heat flux distribution

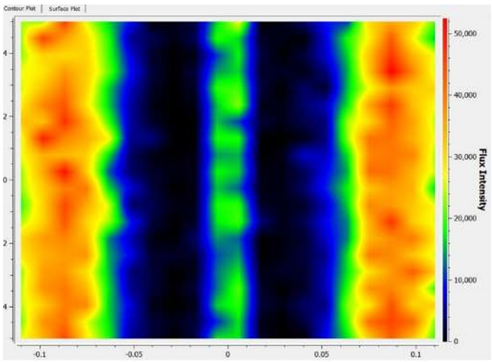


**Fig.8** :flux distribution with integration of lens

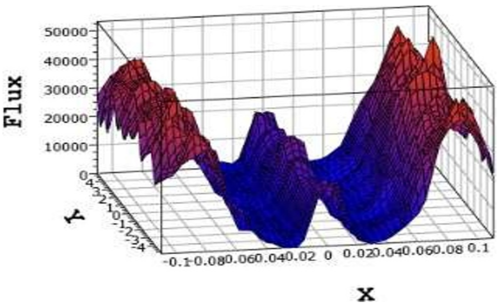


**Fig. 9.** Surface plot of heat flux distribution across the receiver tube with lens

**Table 2** Heat Flux Distribution & Fluid Temperature

| | Upper Half | Lower Half | Temperature |
|---|---|---|---|
| Heat flux without lens | 1000 W/m² | 46625 W/m² | 393K |
| Heat flux with lens | 3600 W/m² | 46625 W/m² | 427K |

## 5 Results and Discussion

### 5.1 Structural analysis results

The parabolic reflector was subjected to a static structural wind load of 2400 N(calculated using Drag Equation) to evaluate its stability. The analysis confirmed no deformation in the reflective sheet under these extreme conditions, demonstrating the exceptional strength and stability of the support system. Maintaining the parabolic shape is critical for optical performance, as even minor deformations can significantly affect focus and efficiency. These findings confirm the structural reliability of the design under high-wind conditions shwon in Fig 10.

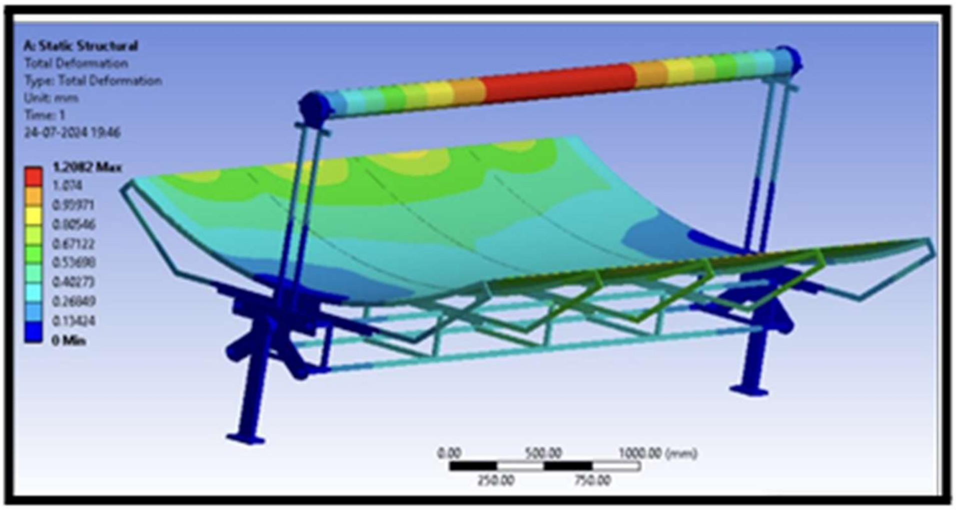


**Fig.10.** Self Weight Structure Analysis

### 5.2 Wind analysis results

The parabolic reflector underwent testing under high wind loads. The results indicate no structural deformation in the reflective sheet, verifying the strength and stability of the system. Maintaining the parabolic geometry is essential, as even minor shape alterations can compromise focus and reduce efficiency. These results validate the design's resilience to extreme environmental conditions and its ability to maintain performance under high-wind stress shown in Figs 11 and 12.

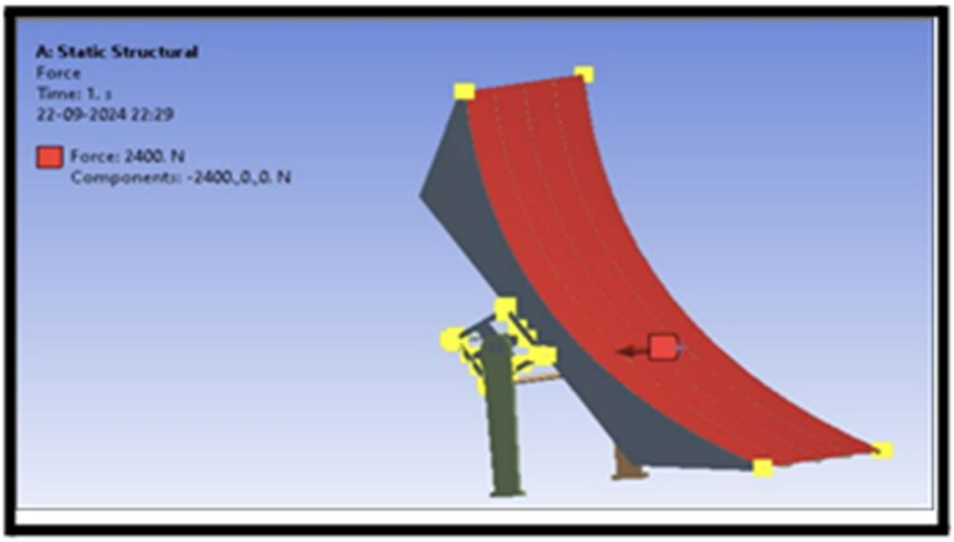


**Fig . 11.** Wind Load Structure Analysis Boundary Conditions

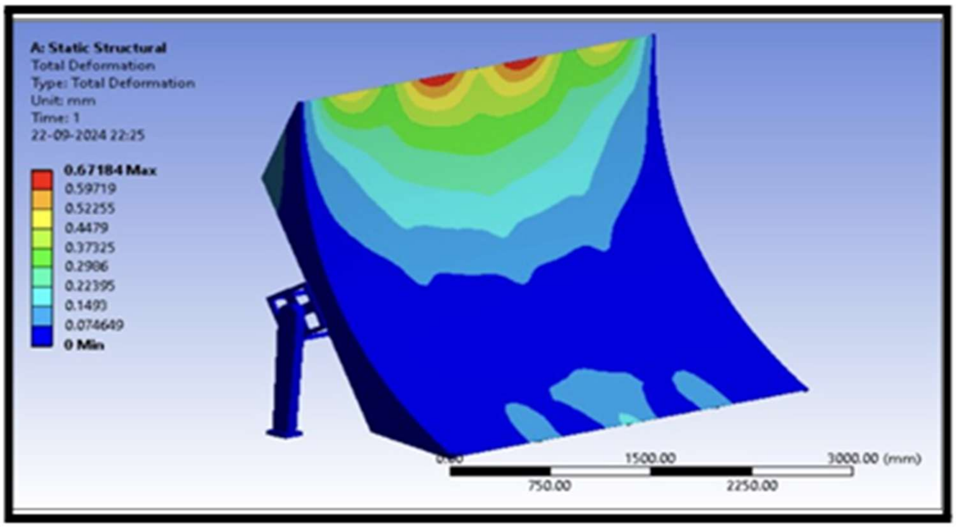


**Fig.12** Wind Load Structure Analysis

## 5.3 CFD RESULTS

The results show a notable improvement in heat distribution and overall system performance with the addition of the plano-convex lens. Without the lens, the upper half of the receiver tube receives only 1000 W/m² of heat flux, while the lower half experiences a much higher 46625 W/m². This imbalance causes uneven heating, leading to thermal stress, material degradation, and lower thermal efficiency. The receiver's maximum temperature without the lens is 393 K, highlighting limited heat absorption in the upper region.

With the plano-convex lens, the heat flux in the upper half increases to 3600 W/m², ensuring more even energy distribution across the receiver's surface. However, the lower half still experiences 46625 W/m², meaning that while high heat concentration remains, the optical enhancement allows for better energy absorption in the upper section. As a result, the maximum receiver temperature increases to 427 K, confirming higher thermal efficiency and improved heat transfer across the system as shown in Figs 13 and 14.

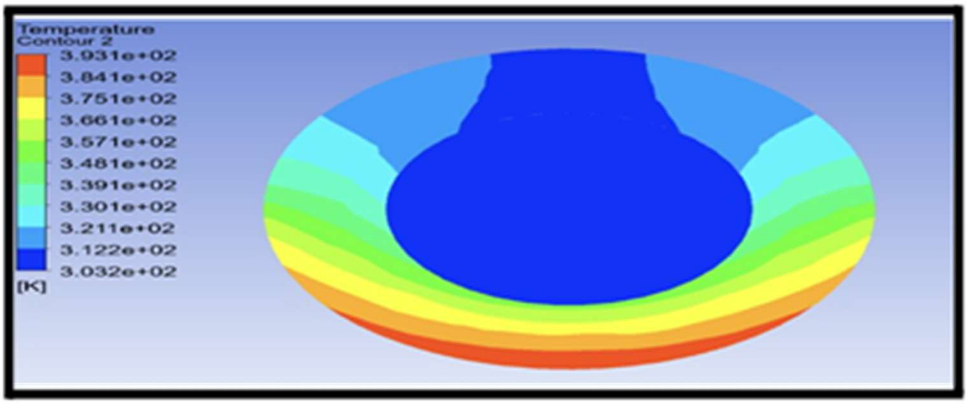


**Fig.13.** Thermal Contour Without Lens

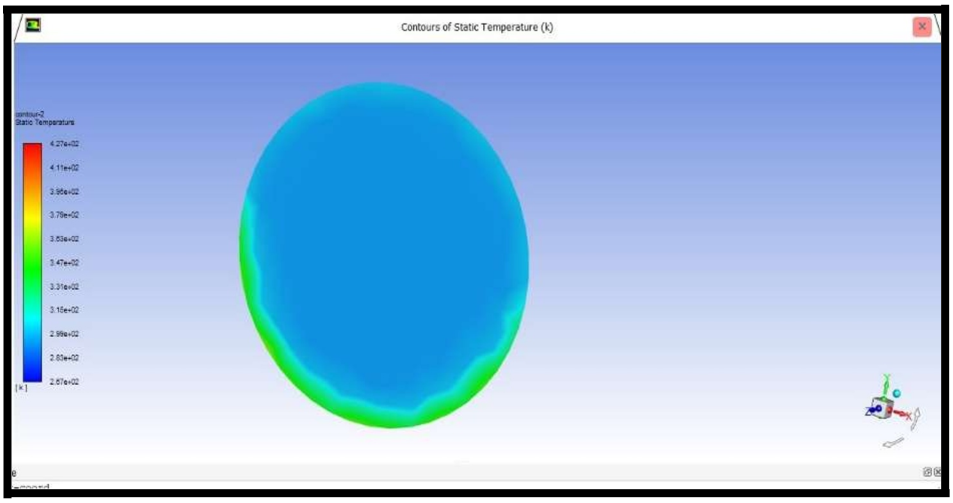


**Fig.14.** Thermal Contour With Lens

## 6 Conclusion

Experiments confirm that adding a plano-convex lens above the receiver tube significantly improves solar flux concentration, leading to a 8.7% increase in thermal efficiency (from 393 K to 427 K). Structural enhancements keep deformation minimal (only 1.2 mm), ensuring that the system maintains optical precision and efficient heat transfer. Wind load tests with a 2400 N force further validate the system's strength and stability, showing no structural deformation even under extreme conditions. These results highlight the effectiveness of the proposed improvements in enhancing PTC performance, making the system more durable and economically viable for solar thermal applications.

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