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# Improving Thermal Efficiency of Solar Collectors through CFD-Based Design and Analysis

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***Abstract**: This project focuses on improving the thermal efficiency of solar collectors through computational fluid dynamics (CFD) modeling and analysis using CATIA design software. The study examines fluid flow and thermal performance in both flat plate collectors (FPC) and parabolic trough collectors (PTC) with air and water as working fluids. The analysis was performed across different times of the day, specifically from 10:00 AM to 2:00 PM, and compared the performance of aluminum and copper materials. The simulations revealed that the output temperatures for both FPC and PTC peaked at 2:00 PM. The FPC reached a maximum temperature of 381K with an inlet water temperature of 334K, showing an increase of 47K, while the PTC achieved 398K with an inlet air temperature of 334K, indicating an increase of 64K. However, as time progressed, both the output temperatures and solar flux decreased. The comparative thermal analysis highlighted that copper exhibited a higher heat flux compared to aluminum, indicating superior thermal performance. These results emphasize the critical role of material selection and design optimization in enhancing the efficiency of solar collectors. The use of CFD-based design and analysis proves essential in developing more efficient and cost-effective solar thermal systems, advancing renewable energy technologies.*

***Keywords:** Computational Fluid Dynamics (CFD), Solar Collectors, Flat Plate Collectors (FPC), Parabolic Trough Collectors (PTC), Thermal Efficiency*

## 1. Introduction

A solar thermal collector harnesses heat by absorbing sunlight. While "solar collector" often refers to devices used for solar hot water heating, it also encompasses large-scale power generation systems like solar parabolic troughs and solar towers, as well as non-water heating devices such as solar air heaters. Solar thermal collectors are categorized into non-concentrating and concentrating types. Non-concentrating collectors have an aperture area (the surface that receives solar radiation) nearly the same as the absorber area (the surface that absorbs the radiation), without any additional components beyond the collector itself. Conversely, concentrating collectors feature a much larger aperture area compared to the absorber area, using mirrors to focus sunlight onto the absorber, and they only capture the direct component of sunlight. Non-concentrating collectors are typically used in residential and commercial buildings for space heating, while concentrating collectors are employed in concentrated solar power plants to generate electricity by heating a heat-transfer fluid that drives a turbine connected to an electrical generator. Flat-plate collectors, the most prevalent solar thermal technology in Europe, consist of an enclosure containing a dark-colored absorber plate with fluid circulation passageways and a transparent cover that allows solar energy to enter the enclosure. The sides and back of the enclosure are usually insulated to minimize heat loss.

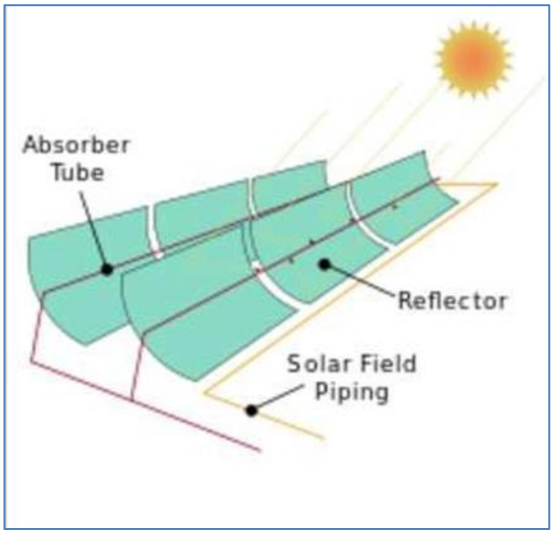


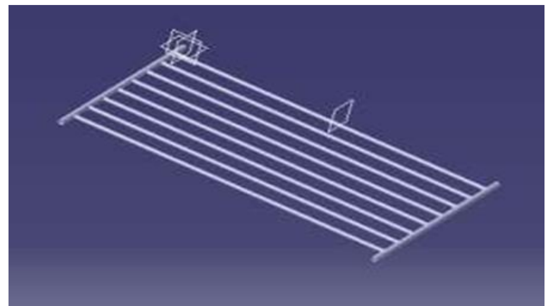

Fig 1 Parabolic trough

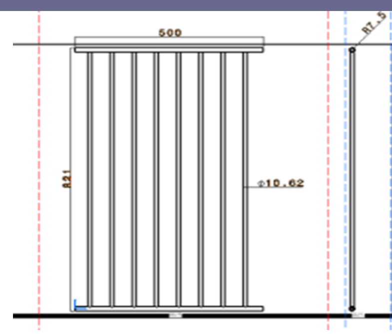
A heat transfer fluid circulates through the absorber's fluid passageways to remove heat from the solar collector. Parabolic trough collectors, generally used in solar power plants, employ a trough-shaped parabolic reflector to concentrate sunlight onto an insulated tube (Dewar tube) or heat pipe at the focal point, which contains a coolant that transfers heat from the collectors to the boilers in the power station.

Improving the thermal efficiency of solar collectors can be achieved through computational fluid dynamics (CFD)-based design and analysis. CFD enables detailed simulation and optimization of fluid flow and heat transfer within the collectors, leading to more effective designs that maximize heat absorption and minimize losses. This approach significantly enhances the performance of both flat-plate and parabolic trough collectors, making solar thermal energy more efficient and cost-effective.

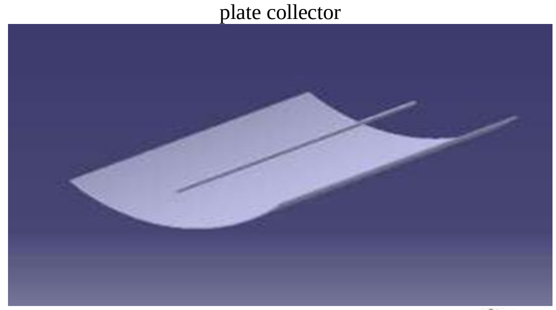
## 2. Modeling and Analysis

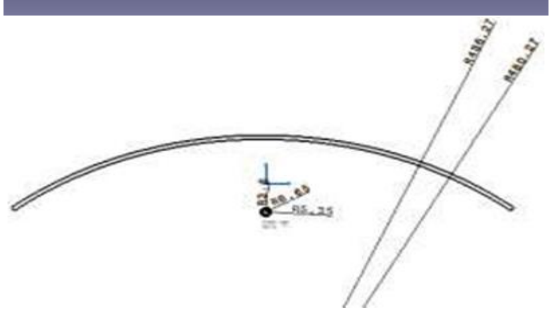
CATIA, an acronym for Computer Aided Three-dimensional Interactive Application, is a leading 3D software used by organizations across various industries, including aerospace, automobile, and consumer products. Developed by Dassault Systèmes, a French engineering giant specializing in aviation, 3D design, 3D digital mock-ups, and product lifecycle management (PLM) software, CATIA is a comprehensive multi-platform suite that encompasses CAD, CAM, and CAE capabilities. In the context of improving thermal efficiency of solar collectors through CFD-based design and analysis, CATIA's advanced modeling and simulation tools are invaluable. By leveraging CATIA, engineers can create precise 3D models of solar collectors, perform detailed computational fluid dynamics (CFD) simulations, and optimize the design for maximum heat absorption and minimal losses. This approach ensures that both flat-plate and parabolic trough collectors achieve higher thermal efficiency, making solar thermal energy systems more effective and cost-efficient.






3D model of flat plate collector 2Dmodel of solar flat plate collector





3D model of parabolic trough 2Dmodel of parabolic trough

ANSYS is capable of conducting both steady-state and transient thermal analyses on solids with thermal boundary conditions. Steady-state thermal analyses determine the effects of constant thermal loads on a system or component. Users often perform a steady-state analysis before a transient thermal analysis to establish initial conditions. Additionally, a steady-state analysis can serve as the final step of a transient thermal analysis once transient effects have diminished. Computational Fluid Dynamics (CFD), a branch of fluid mechanics, employs numerical methods and algorithms to solve and analyze problems involving fluid flows. Computers perform the calculations necessary to simulate the interaction of liquids and gases with surfaces defined by boundary conditions.

Improving the thermal efficiency of solar collectors through CFD-based design and analysis, ANSYS plays a crucial role. By utilizing ANSYS for CFD simulations, engineers can accurately model and optimize the fluid flow and heat transfer within solar collectors. This enables the design of more efficient solar thermal systems, enhancing heat absorption and reducing losses, ultimately making solar energy more effective and cost-efficient.

**Material properties**

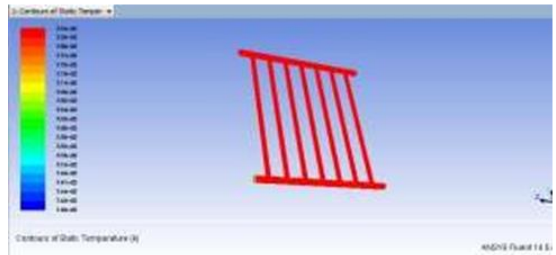
| Description | Density (Kg/m³) | Cp (J/kgK) | Thermal Conductivity (W/m-K) |
|---|---|---|---|
| Glass | 2400 | 670 | 0.96 |
| Copper | 8978 | 381 | 387.6 |
| Insulation Wool | 48 | 670 | 0.05 |
| Air | 1.225 | 1006.43 | 0.0242 |
| Water | 998.2 | 4182 | 0.6 |

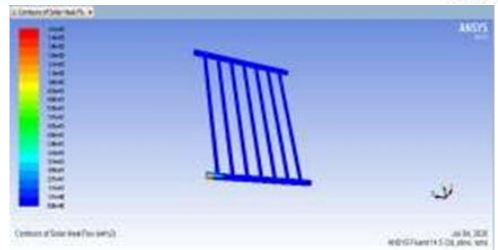
**Boundary conditions**

| Specification | value |
|---|---|
| **At 10 am Temperature (K)** | 307 |
| **At 12 Temperature (K)** | 311 |
| **At 2pm Temperature (K)** | 314 |
| **Mass flow rate(kg/sec)** | 0.015 |

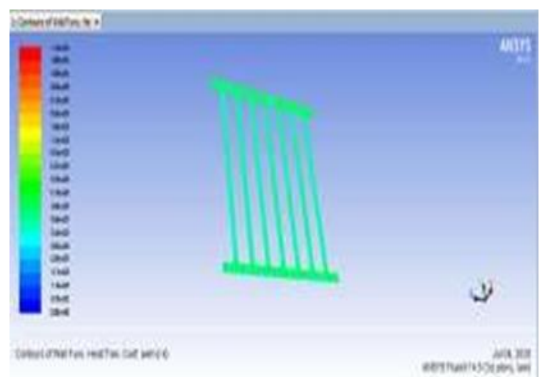
**CFD analysis of Solar Flat Plate Collector**

**At time -2pm**





Temperature Solar heat flux



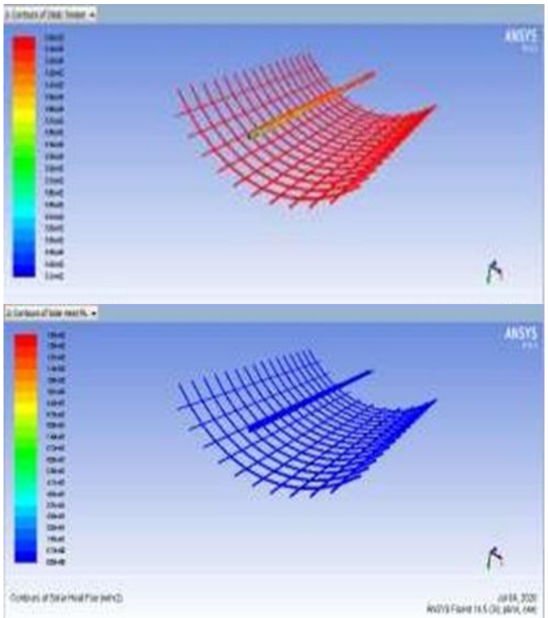
Heat transfer coefficient

**Mass flow rate**

```
          Mass Flow Rate                 (kg/s)
-------------------- --------------------
                 inlet                 0.015
    interior-partbody            0.31217888
                outlet           -0.01493196
         wall-partbody                     0
-------------------- --------------------
                   Net         6.8039633e-05
```

**CFD Analysis of Parabolic Trough**

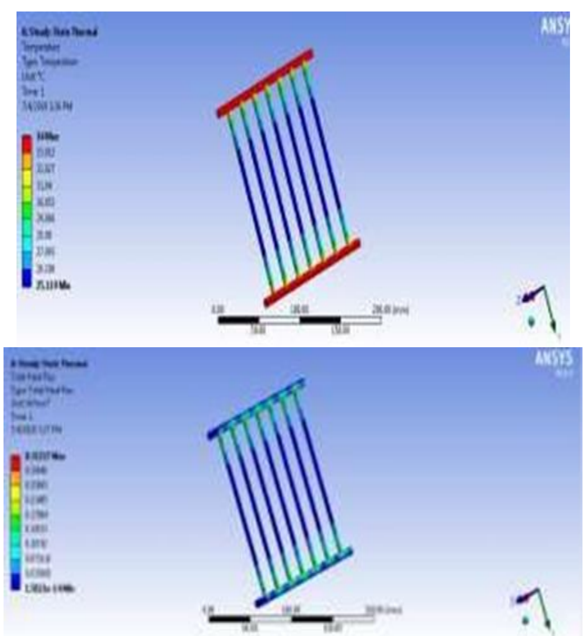
***At time -2pm***



Temperature Solar heat flux

**Thermal Analysis of Solar Flat Plate Collector**

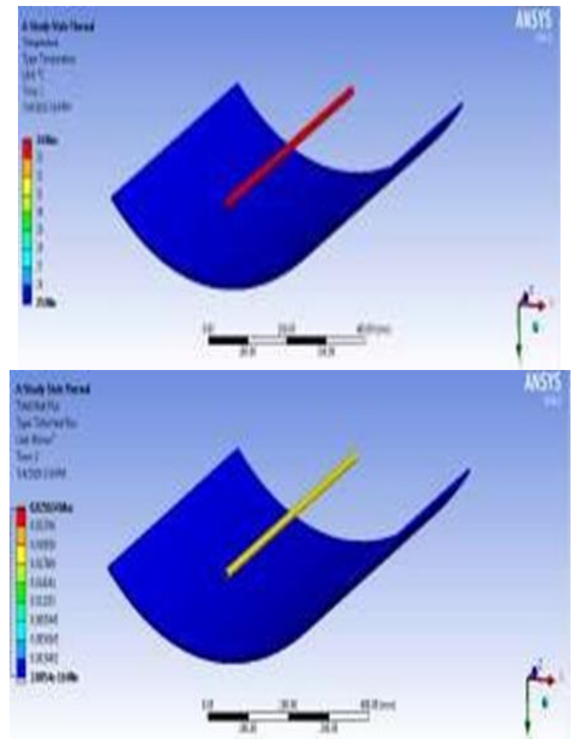
**Material: copper**



Temperature distribution Heat flux

**Thermal analysis of Solar Parabolic Trough**

**Material: Copper**



Temperature distribution Heat flux

## 3. Results & Discussion

Table 1 presents the results of the CFD analysis for a solar flat plate collector, showing temperature and solar heat flux values for two different fluids—air and water—at three distinct times of the day: 10:00 AM, 12:00 PM, and 2:00 PM. For air, the temperature increases from 325K at 10:00 AM to 381K at 2:00 PM, while the solar heat flux rises from 117 W/m² to 148 W/m² over the same period. This indicates a general upward trend in both temperature and heat flux as the day progresses, with the highest values observed at 2:00 PM.

Similarly, for water, the temperature starts at 327K at 10:00 AM and reaches 384K by 2:00 PM. The solar heat flux for water also shows an increase, rising from 118 W/m² to 151 W/m² during the same timeframe. The data reveals that water consistently achieves higher temperatures and solar heat flux compared to air, with temperature differences of 2K to 3K and heat flux differences of 3W/m² to 3W/m² at the corresponding times. These results highlight that water, as a working fluid, performs better than air in terms of both temperature increase and heat absorption in solar flat plate collectors.

Table 1 CFD analysis results of solar flat plate collector

| Fluid | Time | Temperature (k) | Solar heat flux ($w/m^2$) |
|---|---|---|---|
| Air | **10 :00 am** | 3.25e+02 | 1.17e+02 |
| | **12:00 pm** | 3.52e+02 | 1.42e+02 |
| | **2 :00 pm** | 3.81e+02 | 1.48+02 |
| Water | **10 :00 am** | 3.27e+02 | 1.18e+02 |
| | **12:00 pm** | 3.56e+02 | 1.421e+02 |
| | **2 :00 pm** | 3.84e+02 | 1.51e+02 |

Table 2 displays the CFD analysis results for a parabolic trough collector, comparing temperature and solar heat flux for two fluids—air and water—at 10:00 AM, 12:00 PM, and 2:00 PM. For air, the temperature increases from 352K at 10:00 AM to 398K at 2:00 PM, while the solar heat flux rises from 111 W/m² to 142 W/m². This shows a consistent upward trend in both temperature and heat flux as the day progresses, with the highest values occurring at 2:00 PM. In comparison, for water, the temperature starts at 321K at 10:00 AM and reaches 365K by 2:00 PM. The solar heat flux for water increases from 111 W/m² to 142 W/m² over the same period. Although water shows a lower starting temperature and heat flux compared to air, it exhibits a similar rate of increase throughout the day. The temperature difference between air and water ranges from 20K to 33K, with corresponding differences in heat flux of 0W/m² to 3W/m² at each time point. This indicates that while air achieves higher temperatures and heat flux values than water, both fluids show similar trends in heat absorption and temperature rise throughout the day.

Table 2 CFD analysis results of parabolic trough collector

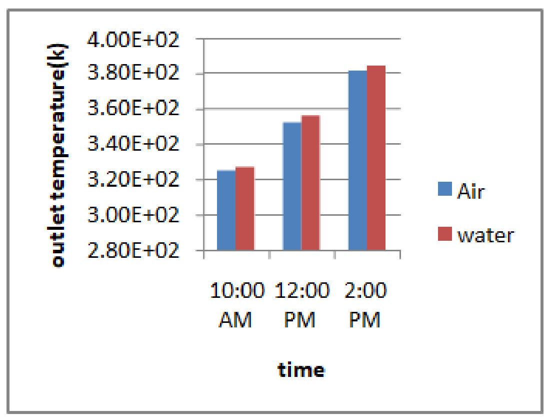
| Fluid | Time | Temperature (k) | Solar heat flux ($w/m^2$) |
|---|---|---|---|
| Air | **10:00 am** | 3.52e+02 | 1.11e+02 |
| | **12:00 pm** | 3.76e+02 | 1.36e+02 |
| | **2 :00 pm** | 3.98e+02 | 1.42e+02 |
| Water | **10:00 am** | 3.21e+02 | 1.11e+02 |
| | **12:00 pm** | 3.45e+02 | 1.35e+02 |
| | **2 :00 pm** | 3.65e+02 | 1.42e+02 |

Table 3 presents the results of the heat transfer coefficient and mass flow rates for solar flat plate collectors (SFPC) and parabolic trough collectors (PTC) using air and water as fluids. For the SFPC, the heat transfer coefficient for air is 460 W/m²-K, with a mass flow rate of 0.0001134367 kg/sec. In contrast, when water is used as the fluid, the heat transfer coefficient significantly increases to 11,400 W/m²-K, while the mass flow rate decreases to 0.0000068309 kg/sec. This indicates that water has a much higher heat transfer efficiency than air in SFPCs, despite having a lower mass flow rate. For the PTC, the heat transfer coefficient for air is 1,180 W/m²-K, with a mass flow rate of 0.00000595 kg/sec. When water is used, the heat transfer coefficient rises to 4,110 W/m²-K, and the mass flow rate increases to 0.0000257 kg/sec. Similar to the SFPC, water demonstrates a higher heat transfer efficiency in PTCs compared to air, along with a higher mass flow rate. Overall, the data shows that water, as a fluid, provides significantly higher heat transfer coefficients for both types of collectors compared to air, albeit with varying mass flow rates. This highlights the superior thermal performance of water over air in solar collector applications.

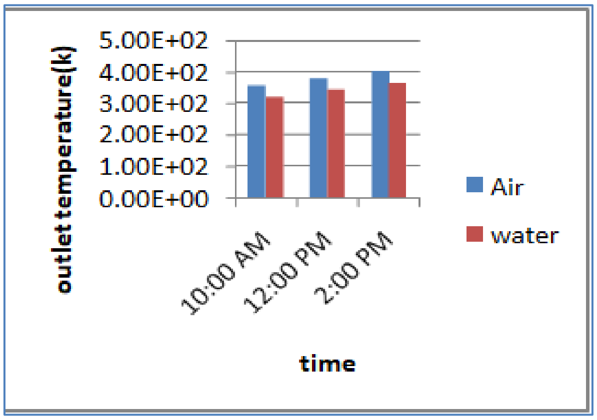
Table 3 results of Heat transfer coefficient and mass flow rates

| Type of collector | Fluid | Heat transfer coefficient ($w/m^2$-k) | Mass flow rate (kg/sec) |
|---|---|---|---|
| **SFPC** | **Air** | 4.60e+02 | 0.0001134367 |
| | **Water** | 1.14e+04 | 0.0000068309 |
| **PTC** | **Air** | 1.18e+03 | 5.95e-06 |
| | **Water** | 4.11e+03 | 2.57e-05 |

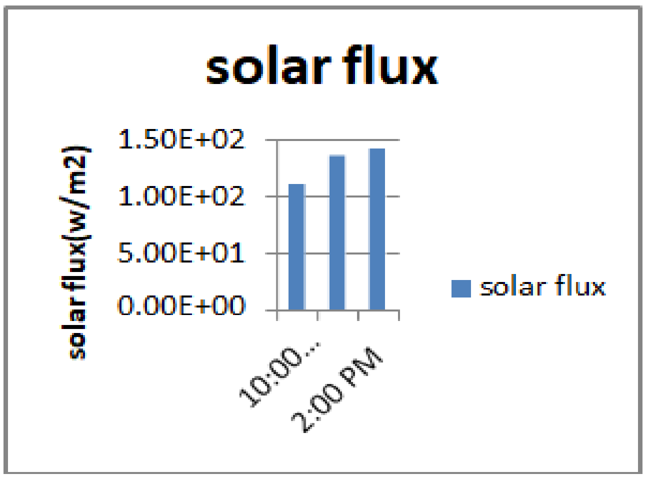
**Graphs**



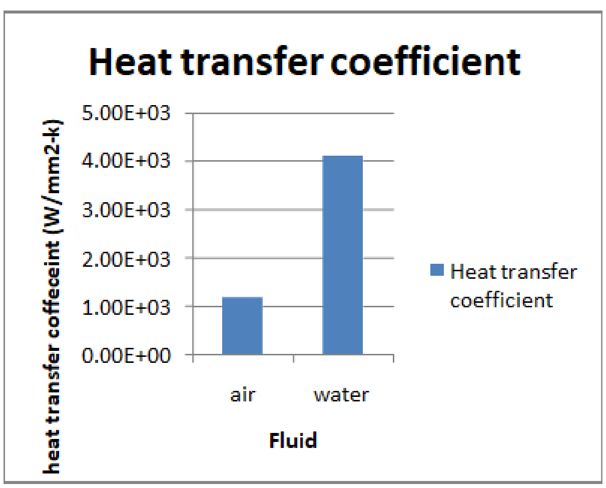

Graph 1 solar flat plate collector results (time Vs outlet temperatures)




Graph 2 Parabolic trough collector results (time Vs outlet temperatures)




Graph 3 time Vs solar flux




Graph 4 Fluids Vs heat transfer coefficients

## 4. Conclusion

In conclusion, this project successfully modeled the fluid flow through flat plate collectors (FPC) and parabolic trough collectors (PTC) using CATIA design software. The thermal and CFD analyses were conducted with air and water as working fluids over different times of the day, focusing on materials like aluminum and copper. The simulations for both FPC and PTC showed that the output temperatures peaked at 2:00 PM, with FPC reaching 381K from an inlet temperature of 334K, and PTC reaching 398K from an inlet temperature of 334K. This demonstrated increases of 47K and 64K, respectively. However, as time progressed, the output temperatures decreased, and solar flux diminished with increasing time. Comparative thermal analysis revealed that copper provides higher heat flux than aluminum alloy, indicating better thermal performance. These findings underscore the importance of material choice and design optimization in enhancing the thermal efficiency of solar collectors. By leveraging CFD-based design and analysis, it is possible to achieve more efficient and cost-effective solar thermal energy systems, contributing to the advancement of renewable energy technologies.

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