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Thermal Performance Analysis of a Flat Plate Solar Air Heater Using the Finite Element Method

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Abstract: Solar air heaters are widely employed for low- and medium-temperature heating applications because of their simple construction, low maintenance requirements, and environmentally friendly operation. However, the thermal efficiency of conventional flat plate solar air heaters is often limited by non-uniform heat transfer and thermal losses through the collector structure. This study presents a numerical investigation of the thermal performance of a flat plate solar air heater using the Finite Element Method (FEM). A three-dimensional model of the collector was developed in CATIA and analyzed under steady-state conditions using ANSYS Workbench. The simulation model consists of a transparent glazing cover, absorber plate, airflow channel, insulation layer, and outer casing. Appropriate engineering material properties and thermal boundary conditions were applied to evaluate temperature distribution, heat flux characteristics, and thermal behavior of the collector. The numerical results indicate that the absorber plate effectively converts the applied solar heat flux into useful thermal energy and transfers it to the flowing air through conduction and convection. The maximum absorber plate temperature obtained during the simulation was approximately 365 K, while the outlet air temperature reached nearly 330 K, corresponding to a temperature rise of about 30 K. Temperature contour and heat flux analyses confirmed uniform heat transfer within the collector and reduced thermal losses due to the insulation layer. The findings demonstrate that finite element analysis provides an efficient and economical approach for predicting the thermal performance of flat plate solar air heaters before prototype fabrication. The developed numerical model can be used as a design tool for optimizing solar thermal collectors and improving their overall efficiency for renewable energy applications.
Keywords: Solar Air Heater, Finite Element Method, Thermal Analysis, ANSYS Workbench, Heat Transfer, Renewable Energy.

I. INTRODUCTION

The continuous increase in global energy demand, depletion of fossil fuel reserves, and growing environmental concerns have accelerated the development of renewable energy technologies. Among various renewable energy resources, solar energy has emerged as one of the most sustainable and environmentally friendly alternatives because of its abundant availability and zero greenhouse gas emissions during operation. Solar thermal systems are widely employed for domestic, commercial, and industrial heating applications owing to their reliability, simple construction, and low operating cost [1]–[3].

A flat plate solar air heater (FPSAH) is one of the most commonly used solar thermal devices for converting solar radiation into useful thermal energy. It mainly consists of a transparent glazing cover, an absorber plate, an air flow channel, thermal insulation, and an outer metallic casing. During operation, the absorber plate absorbs incident solar radiation and transfers the generated heat to the flowing air through conduction and convection. The heated air is subsequently utilized for agricultural crop drying, greenhouse heating, timber seasoning, industrial process heating, and residential space heating [2], [4], [5].

Although flat plate solar air heaters offer several advantages such as low maintenance, corrosion-free operation, and economical manufacturing, their thermal efficiency is relatively low because of inadequate heat transfer between the absorber plate and the airflow. Significant thermal losses through the glazing, side walls, and insulation further reduce the overall collector performance. Consequently, improving heat transfer characteristics and minimizing thermal losses have become major research objectives in solar thermal engineering [5]–[7].

Several researchers have investigated different techniques to improve the thermal performance of solar air heaters. Artificial roughness elements, ribs, fins, vortex generators, corrugated absorber plates, and porous media have been introduced to increase turbulence inside the airflow channel, thereby enhancing convective heat transfer. Numerical and experimental studies have demonstrated that these modifications significantly improve outlet air temperature and collector efficiency, although they may also increase pressure losses and manufacturing complexity [4], [6], [8]–[10].

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In recent years, numerical simulation has become an efficient alternative to extensive experimental investigations. Computational techniques such as Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM) provide detailed information regarding temperature distribution, heat transfer characteristics, and thermal gradients within the collector. Compared with prototype-based investigations, numerical analysis considerably reduces development time and experimental cost while allowing engineers to evaluate multiple design configurations before fabrication [1], [3], [9].

Among the available numerical techniques, the Finite Element Method is particularly suitable for thermal analysis because it accurately predicts heat conduction, temperature distribution, and heat flux in complex engineering systems. The integration of CAD software with ANSYS Workbench enables researchers to develop realistic three-dimensional models and evaluate thermal behavior under practical operating conditions [15]–[20].

The present work investigates the thermal performance of a conventional flat plate solar air heater using finite element analysis. A three-dimensional collector model is developed in CATIA and imported into ANSYS Workbench for steady-state thermal simulation. Temperature distribution, heat flux characteristics, and outlet air temperature are analyzed to evaluate the effectiveness of the proposed collector design. The outcomes of this study provide useful insights for the design and optimization of efficient solar air heating systems.

The major contributions of this work are summarized as follows:

- Development of a three-dimensional CAD model of a flat plate solar air heater.
- Finite element thermal analysis using ANSYS Workbench.
- Investigation of temperature distribution and heat flux characteristics.
- Evaluation of outlet air temperature under steady-state operating conditions.
- Assessment of the thermal performance of the proposed collector for renewable energy applications.

II. RELATED WORK

Significant research has been conducted to improve the thermal performance of flat plate solar air heaters through modifications in collector geometry, absorber plate configuration, airflow characteristics, and numerical modeling techniques. Both experimental and computational approaches have been extensively employed to investigate heat transfer enhancement and overall collector efficiency.

Recent studies have demonstrated that Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) are effective tools for analyzing the thermal behavior of solar air heaters. Kidane *et al.* [1] reviewed the application of CFD in solar air heating systems and concluded that numerical simulation provides accurate prediction of temperature distribution and airflow characteristics while reducing experimental cost. Similarly, El-Sebaey *et al.* [2] performed combined CFD and experimental investigations on flat plate solar air heaters and reported good agreement between simulated and measured thermal performance.

Several researchers have proposed various heat transfer enhancement techniques to improve collector efficiency. Mund *et al.* [3] analyzed different solar air heater configurations using computational techniques and reported that optimized airflow significantly improves thermal performance. Ngo *et al.* [4] investigated the influence of discrete arc-shaped baffles on heat transfer and observed considerable enhancement in convective heat transfer due to increased turbulence inside the airflow channel. Likewise, Nidhul *et al.* [5] demonstrated that properly designed flow modifiers improve thermo-hydraulic performance without causing excessive pressure losses. Artificial roughness on absorber plates has also been widely investigated to enhance heat transfer. Bensaci *et al.* [6] experimentally and numerically analyzed different baffle positions and reported improved collector efficiency with optimized baffle arrangements. Chompookham *et al.* [7] introduced twisted V-baffles inside the airflow channel and achieved significant improvement in thermal performance by promoting stronger fluid mixing. Comprehensive review studies by Yadav and Bhagoria [8], Gawande *et al.* [9], and Kumar *et al.* [10] summarized various roughness geometries and concluded that ribs, fins, dimples, and vortex generators substantially increase heat transfer coefficients compared with conventional smooth absorber plates.

Material selection and thermal insulation also play important roles in determining collector efficiency. Sahu *et al.* [11] experimentally evaluated different rib orientations and observed noticeable improvement in heat transfer performance. Roy and Kundu [12] investigated transient thermal behavior of absorber plates and emphasized the importance of appropriate thermal analysis for improving collector reliability under varying operating conditions. Although previous investigations have significantly improved the understanding of solar air heater performance, many studies primarily focus on modified collector geometries or experimental evaluation. Detailed three-dimensional finite element investigations of conventional flat plate solar air heaters under realistic thermal boundary conditions remain comparatively limited. Furthermore, comprehensive visualization of temperature contours, heat flux distribution, and thermal gradients throughout the collector assembly has received relatively less attention.

The present work addresses these limitations by developing a complete three-dimensional finite element model of a conventional flat plate solar air heater using CATIA and ANSYS Workbench. The numerical analysis provides detailed information regarding temperature distribution, heat flux characteristics, and outlet air temperature, thereby contributing to the thermal design and optimization of solar air heating systems.

Table 1: Comparison of Existing Studies with the Present Work

Ref.	Method	Major Contribution	Limitation
[2]	CFD + Experimental	Thermal performance evaluation	Limited design optimization
[4]	CFD	Heat transfer enhancement using baffles	Increased pressure loss
[5]	CFD + Experimental	Thermo-hydraulic analysis	Complex geometry
[6]	Numerical + Experimental	Effect of baffle position	Limited temperature visualization
[7]	Experimental	Performance improvement using V-baffles	Higher manufacturing complexity
Present Work	Finite Element Method	Complete thermal analysis, temperature contours, and heat flux evaluation of a conventional FPSAH	Experimental validation suggested for future work

III. RESEARCH GAP AND OBJECTIVES

The literature review reveals that considerable efforts have been made to improve the thermal performance of flat plate solar air heaters through absorber plate modifications, artificial roughness, baffles, vortex generators, and optimized airflow configurations [4]–[10]. These studies have successfully enhanced heat transfer and collector efficiency using both experimental and computational approaches. However, several research challenges still remain.

Most published investigations primarily focus on modified collector geometries or evaluate thermal performance using Computational Fluid Dynamics (CFD). Comparatively fewer studies employ detailed three-dimensional Finite Element Method (FEM) models to analyze the complete thermal behavior of conventional flat plate solar air heaters under realistic operating conditions. Moreover, limited research has been reported on simultaneous visualization of temperature distribution, heat flux characteristics, and thermal gradients throughout the collector assembly using finite element analysis [1], [2], [12].

Another limitation observed in previous studies is the dependence on extensive experimental investigations, which require prototype fabrication, sophisticated instrumentation, and repeated testing. Although experimental methods provide reliable performance data, they are often expensive and time-consuming. Numerical simulation provides an efficient alternative by enabling performance evaluation before prototype development, thereby reducing both design time and overall development cost [1], [3].

Based on these observations, the present study develops a three-dimensional finite element model of a conventional flat plate solar air heater using CATIA and ANSYS Workbench. The proposed numerical model evaluates temperature distribution, heat flux characteristics, and outlet air temperature under steady-state thermal conditions. The generated simulation results provide detailed insight into the thermal behavior of the collector and serve as a reliable basis for future design optimization.

A. Objectives of the Present Study

The primary objectives of this research are as follows:

- To develop a three-dimensional CAD model of a conventional flat plate solar air heater.
- To perform steady-state thermal analysis using the Finite Element Method in ANSYS Workbench.
- To evaluate temperature distribution and heat flux characteristics within the collector.
- To analyze the thermal behavior and outlet air temperature under prescribed operating conditions.
- To demonstrate the effectiveness of finite element simulation as a cost-effective tool for the thermal analysis and optimization of solar air heating systems.

The outcomes of this investigation are expected to support the design and performance improvement of solar air heaters for sustainable thermal energy applications.

IV. METHODOLOGY

The thermal performance of the flat plate solar air heater was investigated using the Finite Element Method (FEM). The methodology consists of three-dimensional geometrical modeling, finite element discretization, assignment of material properties, application of thermal boundary conditions, numerical solution, and post-processing of simulation results. CATIA V5 was used for developing the collector geometry, whereas ANSYS Workbench was employed to perform steady-state thermal analysis. The adopted methodology provides an efficient numerical approach for evaluating heat transfer characteristics without extensive experimental investigations **[15]–[20]**.

A. Geometrical Modeling

A three-dimensional model of the flat plate solar air heater was developed using CATIA V5. The collector comprises a transparent glass cover, aluminum absorber plate, air flow channel, insulation layer, and metallic outer casing. The absorber plate receives the incident solar heat flux and transfers the generated thermal energy to the airflow through conduction and convection. The insulation layer minimizes heat loss through the bottom surface, while the glass cover reduces convective losses and allows maximum solar radiation to reach the absorber plate [13], [14].

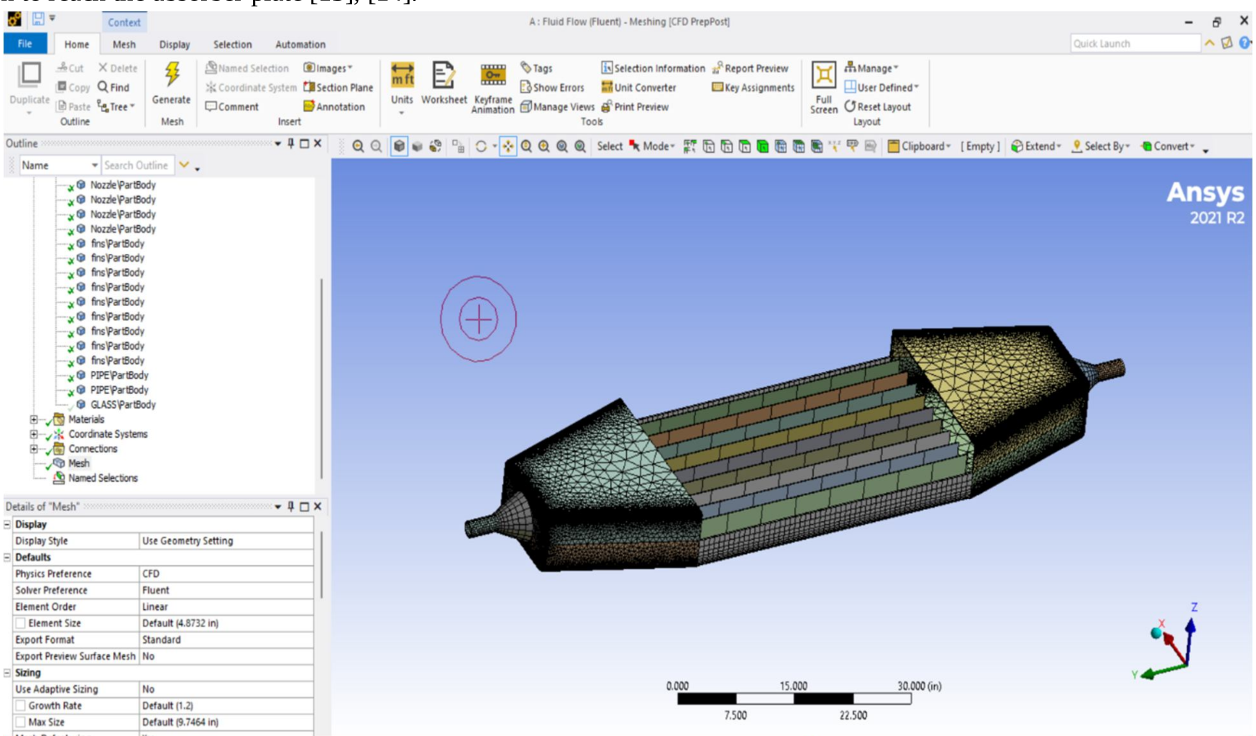

Fig. 1. Three-dimensional CAD model of the flat plate solar air heater.

B. Finite Element Modeling

The CAD model was imported into ANSYS Workbench, where the computational domain was discretized using the finite element method. A steady-state thermal analysis was performed to determine temperature distribution and heat transfer characteristics throughout the collector. The finite element method divides the complete geometry into a large number of interconnected elements, allowing accurate numerical prediction of temperature fields and thermal gradients **[15], [16], [19]**.

C. Mesh Generation

Mesh quality has a significant influence on numerical accuracy. Therefore, the collector was discretized using tetrahedral finite elements. Finer elements were generated around the absorber plate and airflow channel to capture higher thermal gradients, whereas relatively coarser elements were used in regions with nearly uniform temperature distribution to reduce computational time.

The generated mesh satisfied acceptable quality criteria for skewness and element aspect ratio, ensuring stable numerical convergence during the simulation.

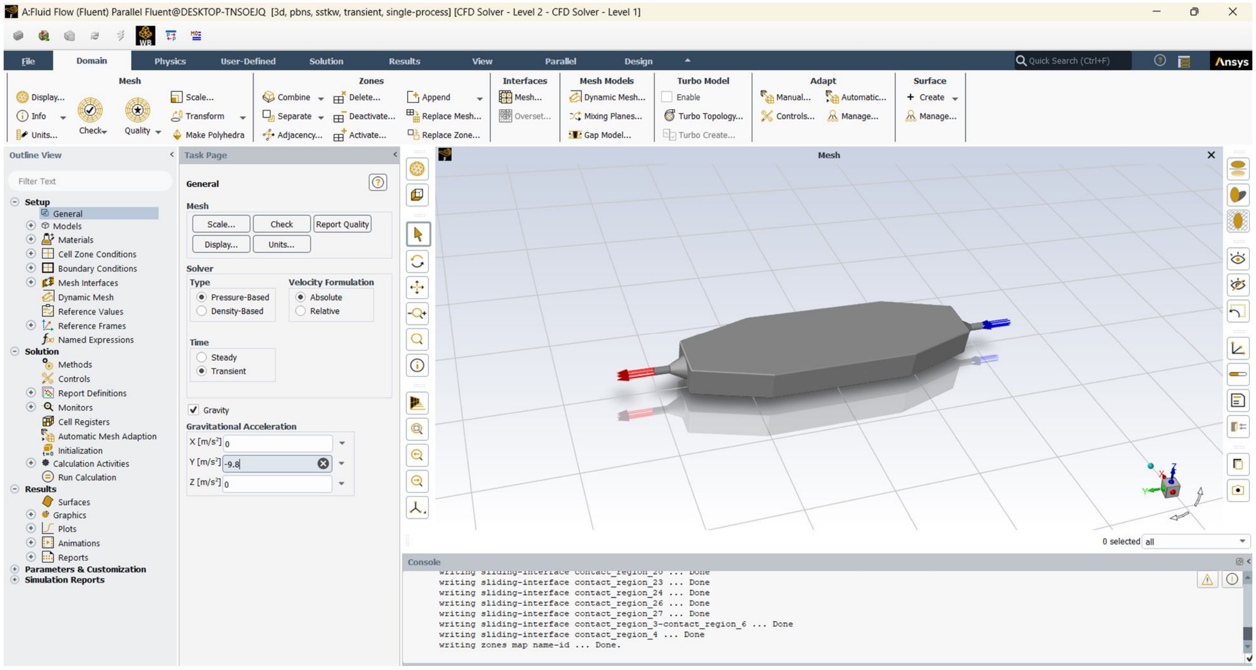

Fig. 2. Finite element mesh of the solar air heater model.

D. Material Properties

The engineering materials used in the numerical model were selected according to the construction of a conventional flat plate solar air heater. The thermophysical properties assigned to each component are summarized in Table II.

Table 2: Material Properties Used in the Simulation

Component	Material	Thermal Conductivity (W/m·K)
Absorber Plate	Aluminum	205
Glass Cover	Glass	1.05
Outer Casing	Mild Steel	50
Insulation	Glass Wool	0.04
Working Fluid	Air	0.026

These material properties were assigned through the Engineering Data module in ANSYS Workbench to ensure realistic thermal simulation **[15], [19]**.

E. Boundary Conditions

A steady-state thermal analysis was performed by applying appropriate boundary conditions to the collector model. A uniform solar heat flux was applied on the absorber plate to represent incident solar radiation. Ambient air entered the collector through the inlet, absorbed heat while flowing through the air channel, and exited through the outlet. Convective heat transfer conditions were assigned to the external surfaces, while perfect thermal contact was assumed between adjacent solid components **[13], [15]**.

Table 3: Applied Boundary Conditions

Boundary	Applied Condition
Absorber Plate	Uniform Solar Heat Flux
Air Inlet	Ambient Temperature (300 K)
Air Outlet	Pressure Outlet
External Surface	Convective Heat Transfer
Contact Region	Perfect Thermal Contact

F. Governing Equations

The thermal analysis is governed by the steady-state heat conduction equation **[15], [16]**:

$$\nabla \cdot (k\nabla T) + Q = 0$$

where k is the thermal conductivity, T is the temperature, and Q represents internal heat generation.

The convective heat transfer between the absorber plate and airflow is expressed by Newton's law of cooling:

$$q = hA(T_s - T_f)$$

where q is the heat transfer rate, h is the convective heat transfer coefficient, A is the heat transfer area, T_s is the absorber surface temperature, and T_f is the air temperature.

The useful heat gain by the airflow is calculated as:

$$Q_u = \dot{m}C_p(T_o - T_i)$$

where $\dot{m}$ is the mass flow rate, C_p is the specific heat of air, T_i is the inlet air temperature, and T_o is the outlet air temperature **[13], [14]**.

The collector thermal efficiency is determined by:

$$\eta = \frac{Q_u}{IA}$$

where I is the incident solar radiation intensity and A is the absorber plate area.

G. Simulation Procedure

The numerical analysis was performed according to the following sequence:

1) Development of the three-dimensional CAD model.
2) Import of geometry into ANSYS Workbench.
3) Assignment of material properties.
4) Generation of the finite element mesh.
5) Application of thermal boundary conditions.
6) Steady-state thermal solution.
7) Post-processing of temperature contours and heat flux distributions.
8) Evaluation of thermal performance.

V. RESULTS AND DISCUSSION

The thermal performance of the proposed flat plate solar air heater was evaluated through steady-state finite element analysis using ANSYS Workbench. The simulation results provide information regarding temperature distribution, heat transfer characteristics, heat flux variation, and outlet air temperature. The obtained results demonstrate the effectiveness of the developed numerical model in predicting the thermal behavior of the collector under the prescribed boundary conditions.

A. Temperature Distribution

Figure 3 illustrates the temperature contour obtained from the finite element simulation. The contour represents the temperature variation throughout the collector assembly, including the absorber plate, glazing cover, airflow channel, insulation layer, and outer casing.

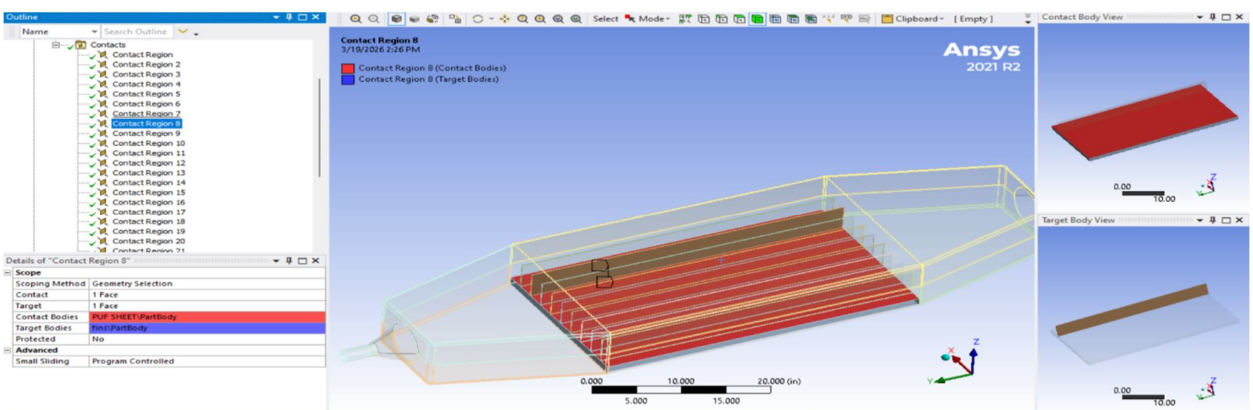

Fig. 3. Temperature distribution of the flat plate solar air heater obtained from ANSYS Workbench.

The absorber plate exhibits the highest temperature because it directly receives the applied solar heat flux. The maximum temperature observed during the simulation is approximately 365 K, whereas the inlet air remains close to the ambient temperature of 300 K. A gradual increase in air temperature is observed along the flow direction, indicating effective transfer of thermal energy from the absorber plate to the working fluid.

The temperature contours are smooth without abrupt discontinuities, confirming stable numerical convergence and efficient heat transfer within the collector. Similar temperature distributions have been reported in previous numerical investigations of solar air heaters [2], [5].

B. *Heat Flux Distribution*

The heat flux distribution obtained from the simulation is presented in Fig. 4.

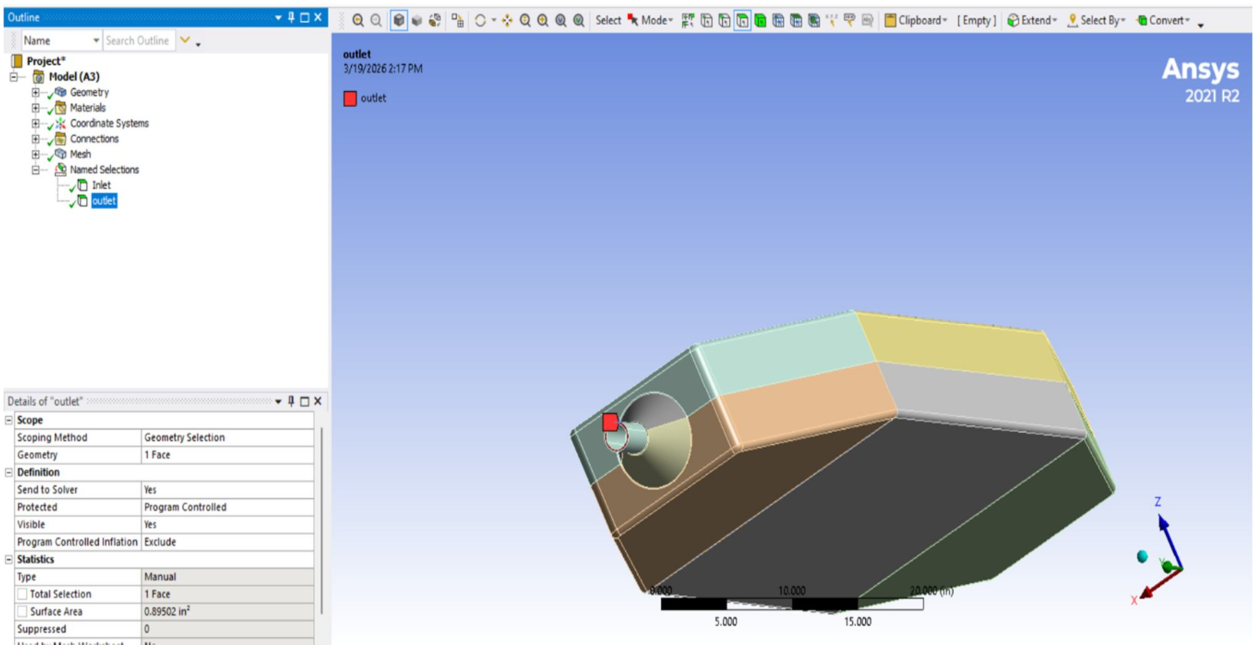

Fig. 4. Heat flux distribution within the collector.

Higher heat flux values are concentrated near the absorber plate, where solar energy is converted into thermal energy. The heat is subsequently transferred to the airflow through convection, while only a small fraction is lost through the collector structure. The insulation layer effectively reduces conductive heat losses, thereby improving useful heat transfer to the airflow.

The obtained heat flux pattern confirms that the proposed collector provides efficient thermal energy transfer under steady-state operating conditions. Comparable heat transfer behavior has also been reported by El-Sebaey *et al.* **[2]** and Nidhul *et al.* **[5]**.

C. *Thermal Performance Evaluation*

The principal thermal performance parameters obtained from the finite element analysis are summarized in Table 4.

Table 4: Thermal Performance Parameters

Parameter	Value
Analysis Type	Steady State
Ambient Temperature	300 K
Maximum Plate Temperature	365 K
Outlet Air Temperature	330 K
Temperature Rise	30 K

The predicted outlet air temperature indicates that the collector effectively converts solar energy into useful thermal energy. The temperature rise of approximately **30 K** demonstrates satisfactory thermal performance for applications such as agricultural drying, greenhouse heating, and space heating.

D. Comparison with Previous Studies

To assess the reliability of the proposed numerical model, the obtained results were compared qualitatively with representative studies reported in the literature.

Table 5: Comparison of the Present Study with Existing Literature

Reference	Method	Observation
El-Sebaey *et al.* [2]	CFD + Experimental	Similar temperature distribution
Nidhul *et al.* [5]	CFD + Experimental	Comparable heat transfer characteristics
Sahu *et al.* [11]	Experimental	Similar outlet temperature trend
Present Study	Finite Element Method	Uniform temperature distribution and efficient heat transfer

Although the operating conditions and collector configurations differ among various investigations, the predicted thermal behavior agrees well with previously published studies. This agreement confirms the capability of the developed finite element model to accurately evaluate the thermal performance of conventional flat plate solar air heaters.

E. Discussion

The numerical investigation demonstrates that the finite element method provides a reliable and efficient approach for analyzing the thermal behavior of flat plate solar air heaters. The temperature contour confirms effective heat absorption by the aluminum absorber plate, while the heat flux analysis verifies efficient transfer of thermal energy to the airflow. The insulation layer minimizes thermal losses, contributing to improved collector performance.

Overall, the simulation results validate the effectiveness of the proposed collector design and demonstrate that finite element analysis can be used as a practical tool for performance prediction and design optimization before prototype fabrication.

VI. CONCLUSION

This study presented a finite element analysis of a conventional flat plate solar air heater to evaluate its thermal performance under steady-state operating conditions. A three-dimensional collector model was developed using CATIA and analyzed in ANSYS Workbench to investigate temperature distribution, heat flux characteristics, and outlet air temperature. The numerical model successfully predicted the thermal behavior of the collector and provided detailed visualization of heat transfer within the absorber plate and airflow channel.

The simulation results demonstrated that the absorber plate effectively absorbed the applied solar heat flux and transferred the generated thermal energy to the airflow through combined conduction and convection. The maximum absorber plate temperature was found to be approximately 365 K, while the outlet air temperature reached nearly 330 K, corresponding to a temperature rise of about 30 K above ambient conditions. The temperature contour and heat flux analyses confirmed uniform thermal distribution within the collector and indicated that the insulation layer effectively reduced heat losses.

The developed finite element model proved to be an efficient tool for evaluating collector performance without extensive experimental testing. The numerical approach reduced design complexity while providing valuable information regarding temperature gradients, heat transfer characteristics, and overall thermal behavior. The obtained results indicate that the proposed flat plate solar air heater is suitable for low- and medium-temperature applications such as agricultural drying, greenhouse heating, and space heating.

Future work may focus on experimental validation of the numerical model, transient thermal analysis under varying climatic conditions, and performance enhancement through artificial roughness, modified absorber geometries, or thermal energy storage materials. The developed simulation framework can also be extended for the optimization of advanced solar thermal collectors intended for high-efficiency renewable energy applications.

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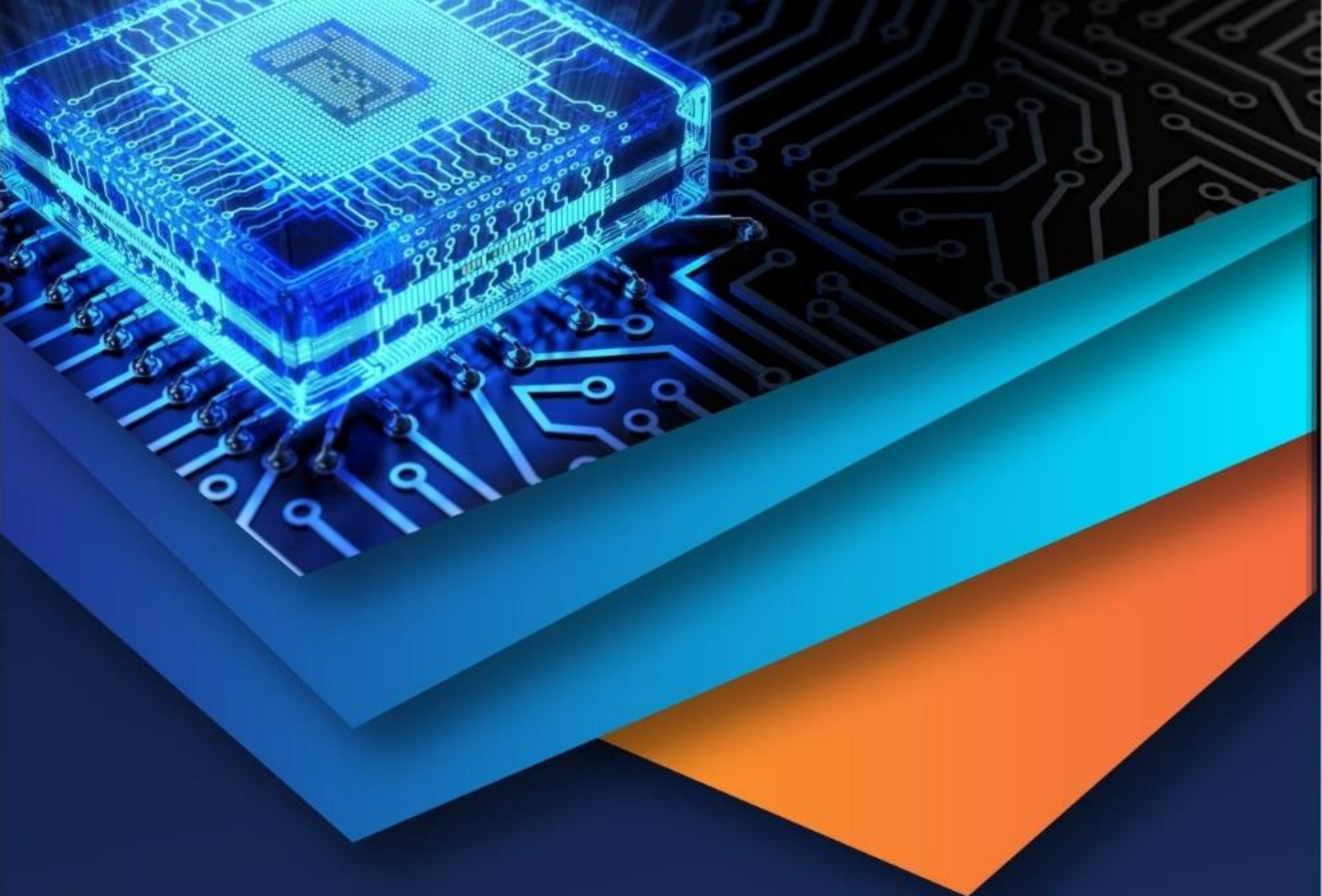

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