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# Numerical Analysis of Heat Transfer and Flow Characteristics in A Semi Cylindrical Solar Air Heater

B. A. Abdukarimov 1
S. A. Mirzayev 2
PhD, Head of the department of Electronics and Instrumentation,
Department of Electronics and Instrumentation,
Fergana state technical university, Fergana, Uzbekistan 1
PhD Student, Department of Electronics and Instrumentation,
Fergana state technical university, Fergana, Uzbekistan 2

**Abstract**
**In this article, a numerical investigation will be conducted on the properties of heat transfer and flow in a semi-cylindrical solar air heater through COMSOL Multiphysics. A three-dimensional model was created to investigate the relationship between heat performance, air flow and solar energy absorption. The convective heat transfer coefficient, useful energy gain, and air temperature were some of the key performance parameters that were developed and executed using user-defined variables in COMSOL. In order to simulate realistic operating conditions, the simulation was performed at the inlet velocity of 0.01 m/s, with the variation of solar radiation within the time periods of 08:00 to 17:00. It was also in the model that the natural convection heat loss on the outer surface of the collector was taken into account. The findings indicate that the semi-cylindrical design is more effective in heat transfer and increase in air temperature hence, increased energy usage efficiency than the conventional design. The established model is an effective computational aid in making predictions on performance and the design optimization of solar air heaters.**

**Keywords: Semi-cylindrical solar air heater, Heat transfer characteristics, Fluid flow analysis, Convective heat transfer coefficient, Thermal efficiency optimization, Numerical modelling of solar collectors, Useful heat gain, Renewable energy applications.**

## Introduction

Energy is a central factor in industrial development and economic growth; however, reliance on limited fossil fuels has led to severe environmental pollution and disruptions of the natural life cycle on Earth. In this regard, renewable energy plays a crucial role in promoting sustainable development, as it supports long-term economic growth, reduces greenhouse gas emissions, enhances energy security, stimulates technological advancement, creates jobs, and contributes to both environmental protection and economic stability [1].

Solar air heaters (SAHs) represent a promising renewable energy technology that utilizes solar radiation to produce hot air, thereby reducing environmental pollution. Compared to other solar energy conversion systems, SAHs offer several advantages, such as low initial investment, minimal automation requirements, and reduced maintenance costs, which can be attributed to their relatively simple design [2]. However, traditional flat-plate solar air heaters exhibit relatively low efficiency, primarily due to the limited volumetric specific performance of the air mass and the relatively low heat exchange temperature between the absorber plate and the circulating air in the duct [3].

Over the last two decades, various methods to enhance the thermal efficiency of SAHs have been investigated, leading to significant advancements in research. Numerous approaches aimed at improving convective heat transfer have been reported, including the use of ribs, baffles, fins, and other turbulence-promoting elements [4,5]. For example, E.M.S. El-Said et al. [6] investigated a tubular swirl-flow solar air heater (SF-SAH) that incorporated a semi-cylindrical absorber plate with fin modules to improve the thermo-hydraulic performance of the design. Both radial and longitudinal fins were studied, and the results demonstrated that radial fins outperformed longitudinal fins as well as plain ducts in terms of efficiency. The optimal configuration, consisting of five radial fins with a maximum flow rate of 0.050 Mkg/s, achieved thermal and thermo-hydraulic efficiencies of 76.79% and 72.40%, respectively, with a corresponding Nusselt number of 223.64 and a cost of production of 0.0105 USD per kilowatt-hour.

Similarly, K. Nidhul et al. [7] analyzed a solar air heater with semi-cylindrical sidewalls and W-shaped baffles to evaluate energy and exergy efficiency under turbulent flow conditions using computational fluid dynamics (CFD). By systematically reducing the baffle height and pitch for Reynolds numbers ranging from 5000 to 17500, they demonstrated that rounded duct corners reduce vortices while simultaneously promoting turbulence. Their results showed that the modified configuration achieved Nusselt numbers and friction factors 3.24 and 4.03 times higher, respectively, than those of smooth ducts, corresponding to 40.7% and 95.4% increases in thermal and exergetic efficiency. Overall, the semi-cylindrical W-baffle solar air heater outperformed traditional ribbed systems.

Semi-cylindrical geometries, especially when reinforced with internal elements such as ribs or baffles, have the ability to generate secondary flows, promote turbulence, and enhance convective heat transfer[8]. These design features can improve flow uniformity, reduce thermal stratification, and increase the effective utilization of solar energy[9]. A comprehensive understanding of such flow and thermal characteristics enables the establishment of precise performance correlations, optimization of design parameters, and reliable predictions of system efficiency under various operating conditions. Furthermore, these improvements contribute to minimizing exergy losses, enhancing cost-effectiveness, and supporting the global implementation of SAHs in sustainable energy applications[10].

Despite the growing body of literature on flat-plate and rectangular duct SAHs, detailed numerical investigations of semi-cylindrical geometries remain scarce[11]. Conventional designs still suffer from recirculation zones and poor convective mixing, and although enhancement strategies such as ribs and fins have been proposed, the specific performance benefits of semi-cylindrical ducts under realistic solar conditions are not yet fully understood[12].

This study addresses this gap by presenting a numerical analysis of a semi-cylindrical solar air heater using COMSOL Multiphysics to investigate the coupled processes of heat transfer and airflow[13,14]. Unlike traditional flat-plate configurations, the semi-cylindrical design reduces dead zones, promotes turbulence and convective heat transfer, and improves overall collector efficiency[15, 16]. The findings of this work provide new performance correlations and design guidelines that can be applied to optimize SAHs for low-temperature thermal applications such as space heating, crop drying, and pre-heating of ventilation air.

## 2.0 MATERIALS AND METHOD

### 2.1. Geometry configuration

Solar air heater was modelled as a semi-cylindric geometry in order to enhance the ability to absorb the incident solar radiation and the features of air flow. The collector measure 3m in length and 0.3m in height creating the major semi-cylindrical chamber. The black painted absorber surface that has the maximum capacity to absorb as much solar as possible are positioned under the transparent glass cover. The bottom and side walls were insulated to reduce the heat losses.

The system gets air fed into 10 evenly spaced inlet tubes of inner diameter: 0.015 m, and the tubes are arranged at the bottom of the collector. The outlet is on the other side of the chamber and it is made up of a single tube, which has a diameter of 0.03 m, which will make sure that there is constant flow of air along the semi-cylindrical channel. The total area of the absorber was estimated to be 4.512 m 2 and the hydraulic diameter of the flow channel was estimated to be 0.611 m.

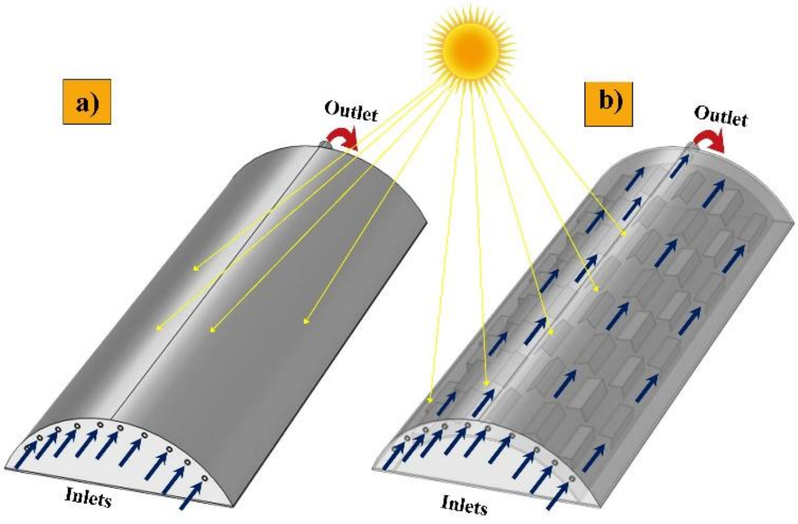

Figure 1 a) Geometric view of Semi-Cylindrical solar air collector, b) Geometric view of Semi-Cylindrical solar air collector with internal demonstration.

The COMSOL Multiphysics was developed to use three-dimensional geometry to accurately model the semi-cylindrical structure and the multi-inlet/outlet design. This design would allow more consistent flow of air, improved use of solar energy and less thermal stratification in the collector.

### 2.2. Finite element solver

The numerical investigation in this paper was done using the Finite Element Method (FEM), a reliable method of solving complex fluid flow and heat transfer problems. In a three-dimensional computational domain that was a model of the solar air heater, the equations of continuity, momentum, and energy were discretized and solved with the FEM.

Figure 2 Generated mesh size for computational domains

To accurately simulate the effects of the boundary layer and the heat transfer characteristics a structured mesh has been developed with finely adjusted grid elements near to the baffles and surfaces of the absorber. The solver applied the segregated solving approach which involved the pressure-velocity coupling applied using the SIMPLE algorithm. To ensure greater accuracy of the solution, the convective terms were discretised using second-order upwind schemes.

Table 1 gives detailed information regarding the mesh structure that has been used by the finite element solver.

Table 1. Finite element solver

| Elements type | Tetrahedra | Mesh vertices |
|---|---|---|
| | 1412237 | 301240 |

The three-dimensional geometry of the semi-cylindrical solar air heater and the resulting finite element mesh are shown in figure 2. The mesh to provide the correct numerical results was refined in areas where the gradients were expected to be high such as the air inlets, outlet, absorber surface, and internal baffles. This enhancement enhances the method of resolving the velocity field and temperature field, which increases the accurate forecast of the flow behaviour and heat transfer traits in the collection area[17].

### 3.0 EQUATIONS AND MATHEMATICS

The distribution of heat inside the solar air collector is a complex physical phenomenon that requires the simultaneous solution of several differential equations. Heat transfer in solids and fluids is described by conduction equations, while the motion of fluids or gases is governed by the

Navier–Stokes equations. Therefore, to comprehensively analyze the processes of flow and heat exchange, the governing equations together with energy balance formulations are employed[18, 19].

In this study, the thermo-hydraulic characteristics of the semi-cylindrical solar air heater were modeled in COMSOL Multiphysics, where the fundamental governing equations and the necessary mathematical relations were implemented as user-defined variables[10].

The heat conduction equation in solid bodies is written as follows.

$$\rho C_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + Q + Q_{ted}; \quad (1)$$

Here, $k$ denotes the thermal conductivity, $Cp$ is the specific heat capacity at constant pressure, $q$ represents the internal heat flux, and  is the amount of heat. Using this equation, the distribution of heat across solid surfaces in contact with each other can be determined. To describe the motion of liquids or gases, the Navier–Stokes differential equation is applied.

$$\begin{cases}
\dfrac{\partial \rho}{\partial \tau} + \dfrac{\partial \rho V_x}{\partial x} + \dfrac{\partial \rho V_y}{\partial y} + \dfrac{\partial \rho V_z}{\partial z} = 0. \\
\rho\dfrac{\partial V_x}{\partial \tau} + \rho V_x \dfrac{\partial V_x}{\partial x} + \rho V_y \dfrac{\partial V_x}{\partial y} + \rho V_z \dfrac{\partial V_x}{\partial z} + \dfrac{\partial p}{\partial x} = \\
= \dfrac{\partial}{\partial x}\left(\nu\rho\dfrac{\partial V_x}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(\nu\rho\dfrac{\partial V_y}{\partial y}\right) + \dfrac{\partial}{\partial z}\left(\nu\rho\dfrac{\partial V_z}{\partial z}\right); \\
\rho\dfrac{\partial V_y}{\partial \tau} + \rho V_x \dfrac{\partial V_y}{\partial x} + \rho V_y \dfrac{\partial V_y}{\partial y} + \rho V_z \dfrac{\partial V_y}{\partial z} + \dfrac{\partial p}{\partial y} = \\
= \dfrac{\partial}{\partial x}\left(\nu\rho\dfrac{\partial V_y}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(\nu\rho\dfrac{\partial V_y}{\partial y}\right) + \dfrac{\partial}{\partial z}\left(\nu\rho\dfrac{\partial V_y}{\partial z}\right); \\
\rho\dfrac{\partial V_z}{\partial \tau} + \rho V_x \dfrac{\partial V_z}{\partial x} + \rho V_y \dfrac{\partial V_z}{\partial y} + \rho V_z \dfrac{\partial V_z}{\partial z} + \dfrac{\partial p}{\partial z} = \\
= \dfrac{\partial}{\partial x}\left(\nu\rho\dfrac{\partial V_z}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(\nu\rho\dfrac{\partial V_z}{\partial y}\right) + \dfrac{\partial}{\partial z}\left(\nu\rho\dfrac{\partial V_z}{\partial z}\right) - F_z; \quad (2)
\end{cases}$$

Here, Vx,Vy,Vz are the velocity components of the flow, ρ is the density, Fz is the gravitational force, ν is the molecular kinematic viscosity of the fluid, and p is the pressure. Using this equation, the velocity and pressure of the fluid flow can be determined. The heat transfer equation in fluids is written as follows.

$$\begin{cases}
\rho C_p \dfrac{\partial T_2}{\partial \tau} + \rho C_p V_x \dfrac{\partial T_2}{\partial x} + \rho C_p V_y \dfrac{\partial T_2}{\partial y} + \rho C_p V_z \dfrac{\partial T_2}{\partial z} = \\
= \dfrac{\partial}{\partial x}\left(k\dfrac{\partial T_2}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(k\dfrac{\partial T_2}{\partial y}\right) + \dfrac{\partial}{\partial z}\left(k\dfrac{\partial T_2}{\partial z}\right) + Q + Q_p + Q_{vd};
\end{cases} \quad (3)$$

Equation (4) is similar to Equation (1), with the main difference being the inclusion of the convective term that accounts for the velocity of the fluid flow.

The convective heat transfer coefficient obtained from convective heat exchange is expressed as follows:

$$h = \frac{k}{D_h} Nu \qquad (4)$$

Here, k is the thermal conductivity coefficient of the working fluid, Nu is the Nusselt number, and Dh is the equivalent diameter, which is defined as follows:

$$D_h = \frac{4Wd}{2(W+d)} \quad (5)$$

Here, d is the equivalent diameter of the channel (m).

## 4.0 RESULTS AND DISCUSSION

COMSOL Multiphysics was used to analysis of thermal and flow behaviour of semi-cylindrical spreading solar air heater under varying solar irradiances and inlet temperature from 08:00 to 16:00. The inlet air velocity was limited to 0,01 m/s, whereas the absorber surface was exposed to a time-dependent heat flux which reproduces the time dependence of the incident radiation belonging to the sun. Convectional losses in the collectors were known as natural and were included at the outer surface of these collectors.

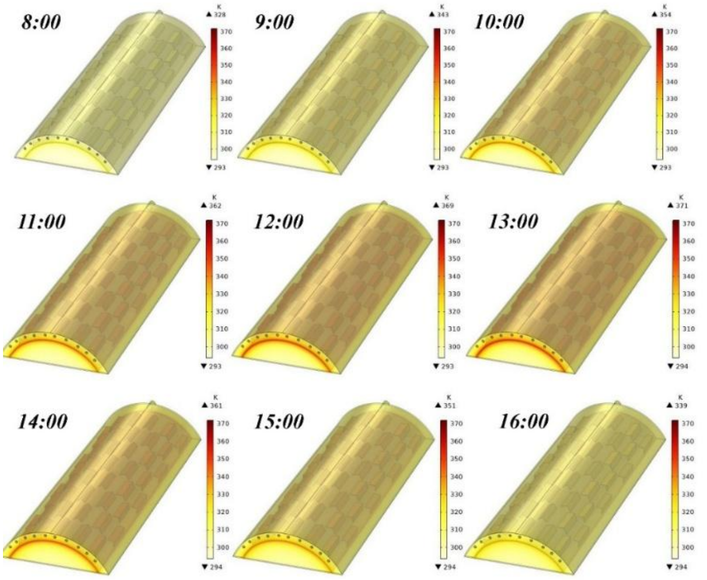

Figure 3 Temperature distribution of solar air collector

Figure 2 shows temperature distribution of the solar air collector at various time of the day that is, 8:00-16:00. The outcomes also vividly show how the absorber surface happens to get heated as time goes by due to the consequent increase of solar irradiance. At 8:00, the temperature is relatively low with the values of around 328 K close to the absorber. During the day, temperature is rising, reaching 343 K and 354 K at 9:00 and 10:00 respectively. The collector records the highest temperature distribution (12:00-13:00) with the maximum values near 371K tendering to the plate of the absorber. Temperature distribution starts to decrease after 13:00 due to the amount of solar energy received. The collector fluctuates a little less at 14:00 with the peak value of 361, 351K at 15:00 and 16:00 respectively. The findings point out that the highest heating goes at solar noon hours when the sun radiates most as compared to the morning and late afternoon hours, which depict lower temperatures.

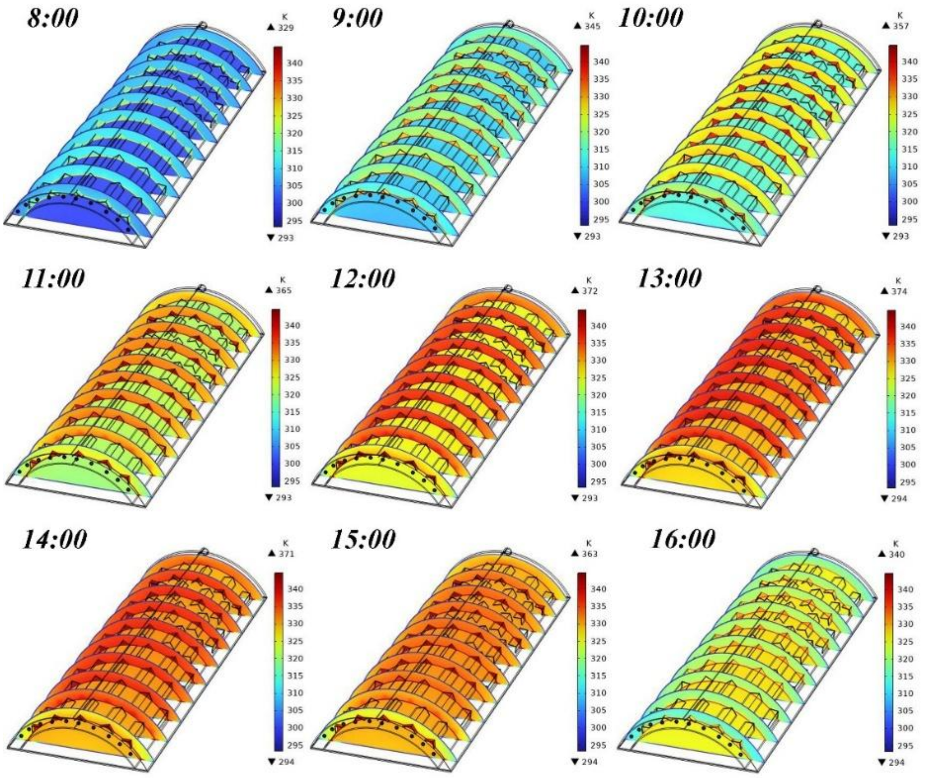

Fig. 3. Temperature distribution of solar air collector

Figure 3 illustrates the temperature profile of solar air collector at various moments of the day on a slice view, thus giving precise understanding of the air temperature profile within channel of the collector. By 8:00 h, the collector has comparatively cool temperatures; they vary between 293 K and 329 K because the sun radiations are low during the early morning. An incorporation of temperature air temperature growth is observed as time moves with a final temperature rise of around 345 K at 9:00am and 357 K at 10:00 am. The slices represent the most evident increase of temperature in the middle of the day (11:00 to 13:00), the maximum temperatures being 365 K to 374 K. That marks the optimum period of solar irradiation whereby the absorber plate would supply of a maximum load of heat to the air flow. The temperature values of 14:00-15:00 h stay rather high (371 K – 363 K), which confirms that the system maintains the good heat retention during the early afternoon. But at 16:00 h, temperature values start decreasing reaching approximately 340 K, which is in-line with the decrease of solar flux. The slice view analysis shows the homogeneous heating of air as it passes through collector channel with the gradient temperature levels also getting steeper near midday. This layout also underlines how efficient the collector was in improving heat transfer on peak sun hour and the anticipated decrease at the end of the afternoon.

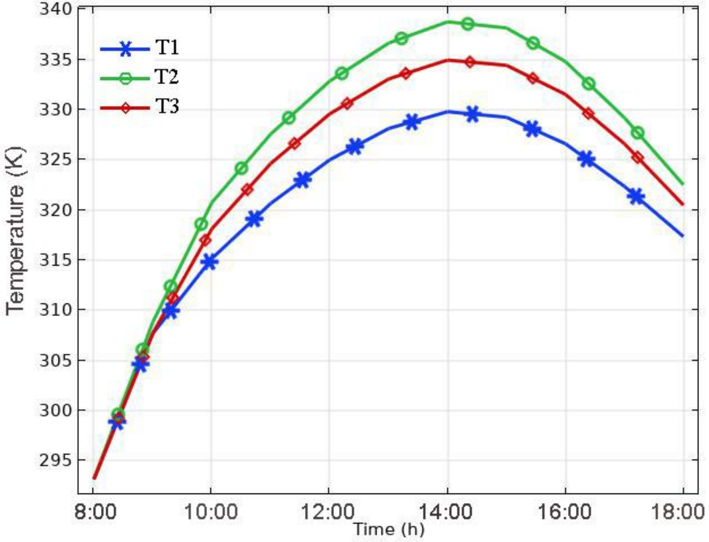

Figure 4 Variation of temperature of air at three different points

Figure 4 illustrates the air temperature change over time within the solar air collector at three different monitoring points (T1, T2 and T3) from 08:00 to 17:00. The records indicate a steady pattern throughout the three points of temperature rising progressively in the early morning as the solar radiation gains strength and gradually rising to high levels in the midday after which it decreases to lower levels in the late afternoons as the solar flux weakens. T2 has the highest temperature of the three indicating that the location has a higher rate of heat absorption and better thermal contact with the absorber surface. T3 comes next and the highest temperatures are about 334 K and the lowest temperatures are found in T1 with the highest density of 330 K. This is a difference in magnitude of airflow exposure and heat transfer capability in different parts of the collector. The recorded behavior confirms higher performance of the collector in the midday (11:00 to 14.00), when the sun rays are the strongest and demonstrates the spatial difference of temperature increase in the system. This type of analysis is necessary to assess flow uniformity, energy gain and the general efficiency of the collector.

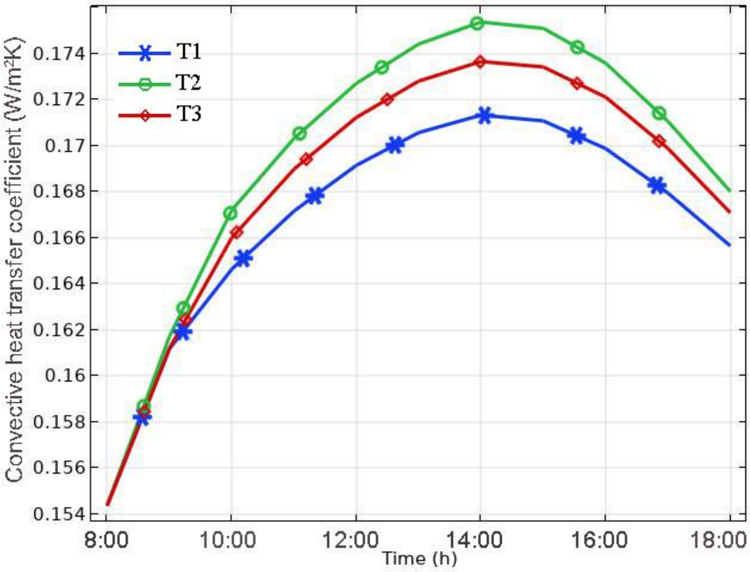

Figure 5 Convective heat transfer coefficients

Figure 5 shows the change of the convective heat transfer coefficient of air within the semi-cylindrical solar air heater at three locations (T1, T2 and T3) during operating hours between 8: 00 to 18: 00. The coefficient is continuously rising in the morning with the growth of the sunlight, and it reaches its maximum between 13:00 and 14:00 then falls in the late afternoon. The maximum values are recorded at T2 then T3 and T1 has always the lowest values. It implies that the central part of the collector has the most successful heat transfer because of the better mixing of air and higher temperatures on the surface.

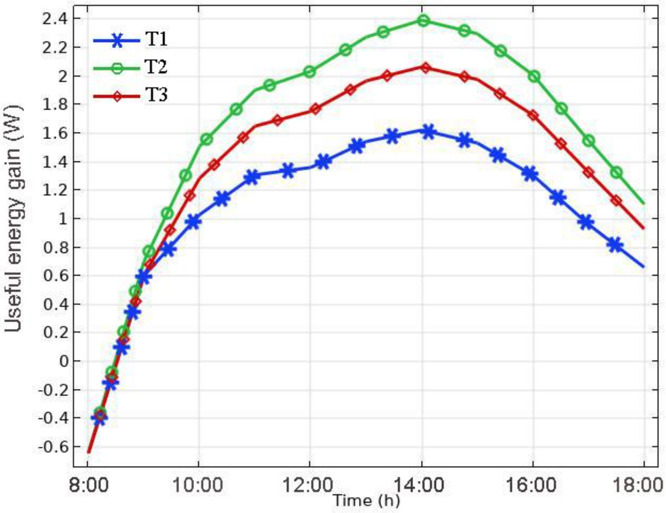

Figure 6 Useful heat gain of air

Figure 6 shows the gain of the useful heat of the air versus time. Just as in the case of the heat transfer coefficient, the useful heat gain increases quickly in the mornings, then peaks around noon and it decreases slowly after that. Optimal heat is gained at a point close to 14:00 at the point T2 showing best thermal performance at this part of the collector. T1 once again depicts the least useful energy gain, and T3 depicts intermediate values. The negative values at 8:00 means that, at the beginning of the experiment, the air temperature within the collector was lower than that of the inlet air which led to a small amount of heat loss before the absorber could sufficiently become hot.

## 5.0 CONCLUSION

The current study analyzed a semi-cylindrical solar air heater, in terms of heat-transfer and fluid-flow properties, by applying a numeric analysis of the heating system to the COMSOL Multiphysics software. The energy and momentum equations governing equations were integrated with user-specified parameters to determine the important performance parameters, such as the spatial distribution of air temperature, the convection heat-transfer coefficient, and the useful heat gain in different conditions of solar-irradiance. The outcomes of the simulation were that there was a gradual rise in air temperature in the collector in the early morning, to its peak around the solar noon, and then began to decrease towards the evening hours. The mid-collector region (T2) had a better performance than the inlet (T1) and the outlet-side (T3) due to better convective mixing and increased absorber heating. Convective heat transfer coefficient and beneficial heat gain had similar temporal characteristics, and attained maximum values from 13:00 to 14:00 as the solar irradiance was at its peak. The transient heat losses were initially negative heat gains at 08:00 before enough heat was drawn into the absorber surface. In general, the semi-cylindrical geometry exhibited good heat-transfer properties, which provided effective heating of air and constant behaviour under the diurnal cycle. Such results highlight the prospects of semi-cylindrical solar air heaters as an effective design in low temperature thermal applications such as space heating, crop drying and pre-heating of ventilating air.

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