# A numerical investigation of a plane solar air heater

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**Abstract.** This study focuses on evaluating the thermal performance of a flat plate solar air heater (SAH) as a key component for harnessing solar thermal energy. The SAH operates by capturing solar energy and utilizing it to heat the air, making it an economically viable, environmentally friendly, and straightforward renewable energy system. MATLAB software is utilized to analyze various performance parameters, such as thermal efficiency, absorber plate area, convective heat transfer coefficient, mass flow rate, insulation thickness, side loss and bottom loss coefficients, and collector efficiency. A specific dimensional model is used for analysis. The influence of these performance parameters on the efficiency of the SAH is explored. Finally, it concludes with some final remarks and proposes work for future advancements for continued study on solar air heaters.

## 1 Introduction

The heavy reliance on fossil fuels to meet global energy demands has undeniable long-term repercussions. At this critical juncture, it is crucial for researchers and decision-makers to explore alternative energy sources that are both technologically viable and environmentally sustainable. Ensuring a reliable and uninterrupted energy supply is essential to support modern lifestyles characterized by mobility, comfort, and prosperity. However, the security of the energy supply should not be taken for granted.

Renewable energy sources, known as clean energy, offer significant potential due to their minimal secondary waste production, low environmental impact, and alignment with societal, economic, and environmental requirements. Embracing renewable energy technologies presents a valuable opportunity to reduce greenhouse gas emissions and mitigate the effects of global warming by replacing traditional energy sources.

Solar power, harnessed from the sun as the primary terrestrial energy source, stands out as a particularly advantageous and accessible form of renewable energy. The solar industry continues to expand with various applications, including photovoltaic technologies, solar air heaters, floating solar farms, solar textiles, solar-powered roads, and solar-powered noise barriers.

The most popular method of utilising the energy of sun is Solar Air Heater (SAH). SAH absorbs sun radiation and converts it into heat by use of a fluid that circulates within the apparatus. As fluid (the air) passes through a solar collector, heat from the sun gradually

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raises its temperature until a specific point. In other terms, it can be said that the system heats the outside cold air before delivering it to the appropriate location. The collector has a glass outer layer that faces the sun. Over the last few decades, preheated air provided to buildings has attracted a lot of attention. It is basically a heat exchanger. It can be used for solar collectors, energy storage, air conditioning, heating houses, and dehydrating agricultural products, among other things.

The rate of convective heat transfers between the air and the plate that absorbs heat has a major effect impact on the SAH's performance. However, there exists a parameter denoted as '*h*' among the absorber plate and the air, which imposes limitations on both the occurrence of SAHs and their thermal efficiency. This '*h*' represents the heat transfer coefficient.

Numerous researchers have proposed alternative approaches to enhance the thermal effectiveness of the SAH. These techniques cover a range of tactics, including adding mirrors to increase solar radiation, redesigning the plate that absorbs radiation to raise the 'h' value, implementing jet impingement, using heat-storage materials, deploying nanofluids, adding baffles or fins, and using vortex generators to increase turbulence. In the pursuit of finding the most suitable geometric configuration, several optimization techniques are employed to establish performance parameters that maximize efficiency. Moreover, the inclusion of surface roughness on the absorber plate enhances turbulence characteristics, contributing further to the improvement of thermal efficiency in the SAH.

These techniques are a selection of the many strategies applied to increase the thermal effectiveness of the SAH. There have been many different results and findings from earlier studies on SAHs.

Olivkar et al. [1] conducted a study on the effects of Sensible Heat Storage (SHS) on the thermal efficiency of SAHs. The results showed that adding SHS components including stones, sand of the desert, metal chips, oil, and gravels can improve thermal efficiency and decrease heat losses. Granular carbon and desert sand were discovered to be the ideal match. Examining different absorber plate geometries, Singh et al. [2] performed experimental investigations using Phase Change Materials (PCM) in a SAH. The results showed that the use of PCM significantly affected the exit air temperature of the SAH, and employing PCM with a flat plate SAH in a cylindrical geometry yielded the highest efficiency.

Abuşka and Kayapunar [3] conducted experimental and numerical investigations on SAHs with conical surfaces. Their findings revealed that conical absorber plates outperformed flat plates in terms of thermal efficiency, with conical surfaces exhibiting the highest Nusselt number. The numerical model results aligned well with the experimental outcomes. In a SAH, Abuşka [4] investigated the thermal properties of an absorber plate with a unique design and a conical surface and contrasted it to a flat absorber plate. The findings showed the significant roles of solar radiation, mass flow rate, and absorber plate surface structure in SAH efficiency, showing a substantial increase in thermal efficiency for conical designs compared to flat ones.

Three SAHs with various lateral shapes (semi-circular, circular, isosceles triangular) were the subject of an experimentaion by Abdullah et al. [5]. The outcomes showed that the circular layout produced the maximum efficiency. Arunkumar et al. [6] analysed design modifications of SAHs to improve thermal performance by considering various SAH arrangements. Their analysis revealed that the integration of turbulators led to enhanced outflow temperatures in the absorber duct. Additionally, fin-shaped turbulators, such as cylindrical and helicoidal types, showed noteworthy improvements in thermal performance.

The inclusion of baffles in SAHs improved thermal efficiency by increasing the heat transmission area. Bensaci et al. [7] presented findings from a numerical and experimental analysis of different baffle positions in SAHs, aiming to enhance thermal and hydraulic efficiency. The revised baffle locations significantly improved the thermohydraulic performance of SAHs. In a research investigation, Skullong et al. [8] evaluated the heat

transfer characteristics in a SAH channel with integrated leaflets and irregular patterns on the surface of the absorber. The outcomes demonstrated that the newly introduced vortex generator caused a change in flow direction, leading to a substantial enhancement in heat transmission. As a result, SAH size reduction was achievable due to the increased heat transfer rate.

Xiao et al. [9] investigated flow parameters and heat transmission performance in SAHs configured with Inclined Trapezoidal Vortex Generators (ITVGs). The findings indicated a remarkable increase in energy and exergy efficiency, by 24% and 31%, respectively, compared to flat SAHs. Singh and Singh [10] evaluated the performance of curved and flat SAHs under various environmental factors. They observed that the exit air temperature and Nusselt number significantly increased when utilizing a curved solar panel compared to a flat plate SAH. Furthermore, the curved SAH exhibited high thermal efficiency and heat content.

The cited literature provides valuable insights into enhancing the thermal performance of SAHs, yet certain aspects have received limited attention thus far. Important areas for further exploration include prioritizing cost-effective insulation materials to prevent heat losses from side and bottom walls, conducting research on optimizing conditions for improved thermal efficiency, focusing on the alteration of absorber duct and plate designs, and investigating the implementation of fin-type turbulators to reduce flow resistance at higher Reynolds numbers, thereby enhancing thermo-hydraulic performance. By addressing these areas, researchers can contribute to the advancement and practical implementation of SAHs in renewable energy systems.

This work merely aims to investigate the impact of various operational factors on the SAH's thermal performance and compare the SAH's thermal performance across various absorber plate geometries.

## 2 Methodology

The thermal performance of a Solar Air Heater (SAH) is analyzed using MATLAB software. The analysis incorporates equations provided by Singh and Singh [10] and Saxena et al. [11], which consider factors such as energy received from the sun, heat received by the circulating air, and different heat losses to the surrounding. These equations form the basis for assessing and evaluating the overall thermal efficiency of the SAH system. The schematic view of SAH is shown in Fig. 1. The length of the SAH is taken as $L$ = 1.83 m and the cross-section dimensions are $W$ = 1.5 m (width) and $H$ = 0.05 m (duct height). On the assumption that the SAH's air channel sidewalls and absorber bottom wall is both thermally insulated, the top side of the SAH is covered with a high transmissivity glass cover (τ) and the plate that houses the absorber has also been coated with a selective coating with high absorptivity (α).

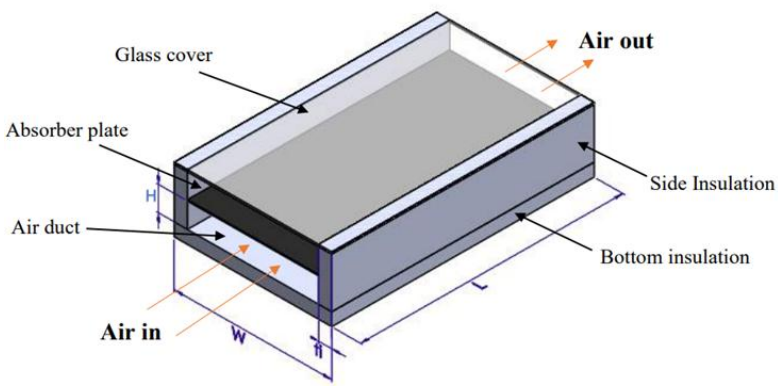


**Fig. 1.** An illustration of the SAH.


**Fig. 2.** The experimental set-up.

A model has been constructed based on the above specifications as shown in Fig. 2.The average solar radiation intensity ($I$) is found to be 712.5 $\mathrm{W/m^2}$ on a particular day in the month of April in Arunachal Pradesh, India with the help of a pyranometer. And the average ambient temperature was found to be around 32℃ at the same place. The wind velocity is measured with anemometer. These operating parameters are shown in Table 1.

For investigation, the following considerations are taken into account: Firstly, the analysis focuses on steady-state conditions as they enable the operation of solar collectors. Secondly, it is assumed that the average air temperature within the ducts and the working temperatures of SAH components remain uniform. Thirdly, the air temperature variations are considered to occur solely in the direction of flow. Fourthly, the ducts are assumed to be free from any leakage. Lastly, the input temperature is maintained within the same range as the ambient temperature. These considerations provide a framework for the examination of the SAH system.

**Table 1.** Operating parameters.

| Parameters | Values |
|---|---|
| Length ($L$) | 1.83 m |
| Width ($W$) | 1.5 m |
| Duct height ($H$) | 0.05 m |
| Emissivity of absorber plate ($\varepsilon_p$) | 0.09 |
| Emissivity of glass cover ($\varepsilon_g$) | 0.84 |
| Wind velocity ($V_w$) | 0.8 m/s |
| Stefan-Boltzmann constant ($\sigma$) | $5.67 \times 10^{-8}$ W/mK |
| Solar Insolation ($I$) | 712.5 $\mathrm{W/m^2}$ |
| Transmissivity ($\tau$) | 0.8 |
| Absorptivity ($\alpha$) | 0.15 |
| Specific heat of air ($C_p$) | $1006 \times (\mathrm{T_a}/293)^{0.015}$ |

### 2.1 Equations for thermal performance

A number of important variables, including sun solar radiation, heat energy received by the moving air, and different forms of heat loss to the atmosphere, are taken into account when calculating the thermal performance parameters in solar heaters. An equation set is used, as shown below [11, 12], to quantify these factors and evaluate the thermal efficiency of the solar heater. These equations offer a thorough framework for assessing the various elements that affect the solar heater's overall thermal performance.

Useful heat gain,

$$Q_U = F_R A_P [I(\tau\alpha) - U_l (T_0 - T_i)] \tag{1}$$

Here, $F_R$ stands for what is known as the heat-removal factor, $A_p$ is the absorber plate area, $U_l$ is total heat loss coefficient, $(\tau\alpha)$ is transmittance-absorbent product of glass cover, $T_o$ is the outlet air temperature and $T_i$ is the inlet air temperature.

Expression for $F_R$ is given by,

$$F_R = \frac{\dot{m} C_p}{U_l A_p}\left[1 - \exp\left\{-\frac{F' U_l A_p}{\dot{m} C_p}\right\}\right] \tag{2}$$

Where $\dot{m}$ is the mass flow rate in kg/s and $C_p$ is the specific heat of air in J/kgK

Collector efficiency factor,

$$F' = \frac{h}{h + U_l} \tag{3}$$

Also, outlet temperature can be expressed as,

$$T_0 = \frac{Q_u}{\dot{m} C_p} + T_i \tag{4}$$

Heat transfer coefficient,

$$h = \frac{Q_u}{A_p (\mathrm{T}_{pm} - T_a)} \tag{5}$$

Where $T_a$ is the ambient temperature in K

Mean plate temperature,

$$\mathrm{T}_{pm} = T_a + F_R I(\tau\alpha)\left[\frac{1 - F_R}{F_R U_l} + \frac{T_0 - T_i}{I(\tau\alpha)}\right] \tag{6}$$

The expression for bottom loss $(U_b)$ and side loss $(U_s)$ coefficients are given as,

$$U_b = \frac{k_i}{t_i} \tag{7}$$

$$U_s = \frac{(L+W)Hk_i}{LWt_i} \tag{8}$$

Where $k_i$ is the thermal conductivity of insulation, $t_i$ is the thickness of insulation, $L$ is the length of the SAH, $W$ is the width of the SAH and $H$ is the duct height.

Therefore, overall heat loss coefficient,

$$U_l = U_b + U_s + U_t \tag{9}$$

Thermal efficiency,

$$\eta_{th} = \frac{Q_u}{IA_p} = F_R\left[(\alpha\tau) - \frac{U_l(T_0 - T_i)}{I}\right] \tag{10}$$

Where $I$ is the amount of radiation from the sun measured in $\mathrm{W/m^2}$.

The various literatures suggest different parameters which can be used to see the variation on the thermal performance of the SAH. Table 2 shows the various parameters that have been chosen for this study to see the effect on the performance of the heater along with their particular ranges.

**Table 2.** Searched range of parameters.

| Parameters | Range |
|---|---|
| Mass flow rate ($m$) | $0.01 - 0.04$ kg/s |
| Overall loss coefficient ($U_l$) | $0 - 10\ \mathrm{W/m^2K}$ |
| Thickness of insulation ($t_i$) | $0.002 - 0.008$ m |
| Absorber plate area ($A_p$) | $0.5 - 2.5\ \mathrm{m^2}$ |

# 3 Results

## 3.1 Temperature

Fig. 3. illustrates the evolution of the inlet temperature and solar radiation with time, while Fig. 4. displays the variations of the inlet temperature and outlet temperature over time. Furthermore, Fig.5. demonstrates the changes in the inlet temperature and mean plate temperature over time. The results indicate that the solar intensity gradually increases from morning hours until reaching a peak value around 1:00 PM, after which it gradually decreases until the end of the measurement period. Similarly, the SAH temperature follows a similar trend, rising over time until approximately 1:00 PM before starting to decline until the conclusion of the reading period. Furthermore, it is shown by the results that heat transfer from the plate that absorbs heat to the air results in greater absorber plate temperatures than the outlet air temperature. As expected, all these SAH temperatures are higher than the ambient temperature.

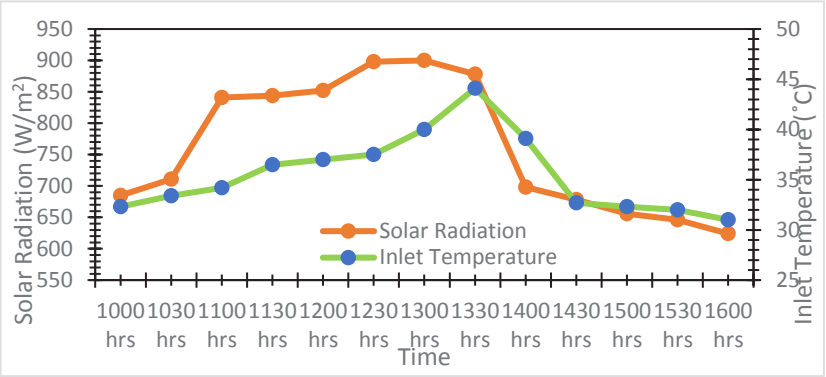


**Fig. 3.** Variation of inlet temperature and solar radiation with time.

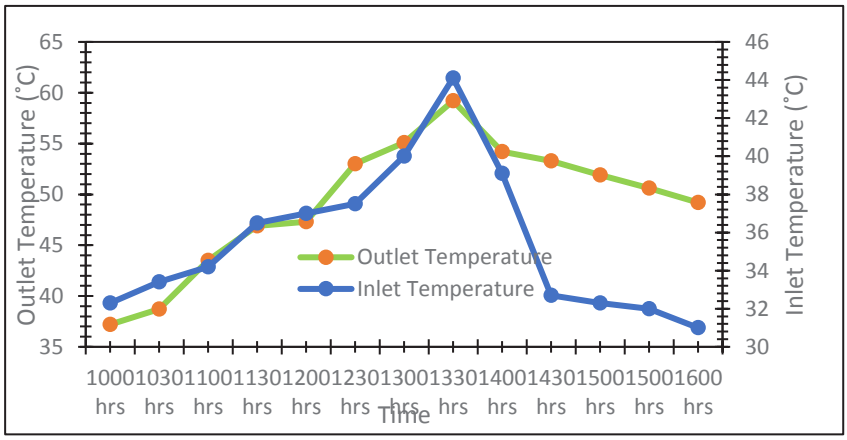


**Fig. 4.** Variation of inlet temperature and outlet temperature with time.

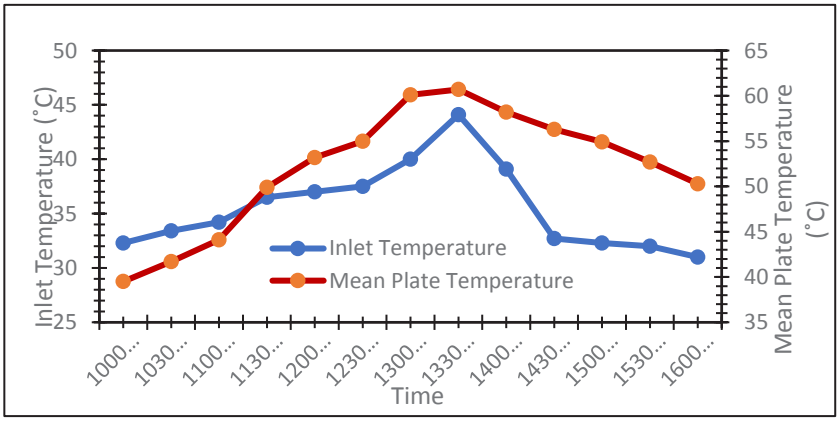


**Fig. 5.** Variation of inlet temperature and mean plate temperature with time.

### 3.2 Simulation results

The impact of various performance parameters on the thermal efficiency of SAH has been studied using the MATLAB software.

Variation of thermal efficiency of SAH for different mass flow rate ($m_1 =$ 0.042 kg/s, $m_2 = 0.048$ kg/s, $m_3 = 0.054$ kg/s, $m_4 = 0.060$ kg/s, $m_5 = 0.068$ kg/s) against varied absorber plate area has been studied, as shown in Fig. 6. It is observed that the nature of graph is hyperbolic. This means $\eta_{th}$ decreases as the $A_p$ increases. It is also observed that for higher mass flow rates the efficiency increases so a greater mass flow rate will enhance the heater's thermal efficiency.

The graph between thermal efficiency and mass flow rate for various solar radiation is linear, as can be observed from the Fig. 7. This suggests that when mass flow rate rises, thermal efficiency does too.

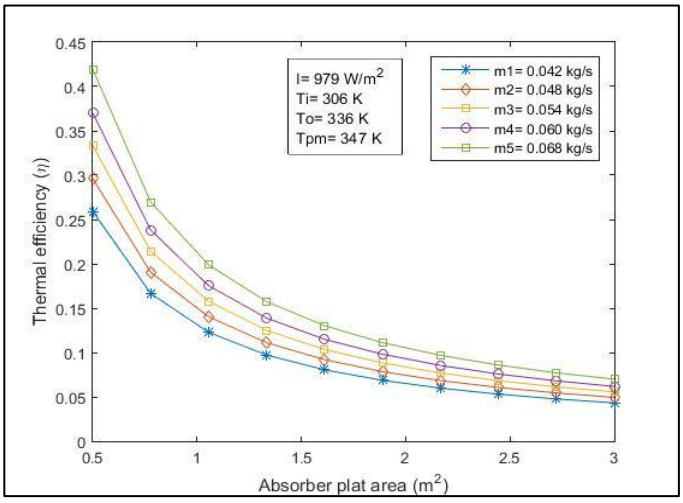


**Fig. 6.** Variation of thermal efficiency vs absorber plate for different mass flow rate.

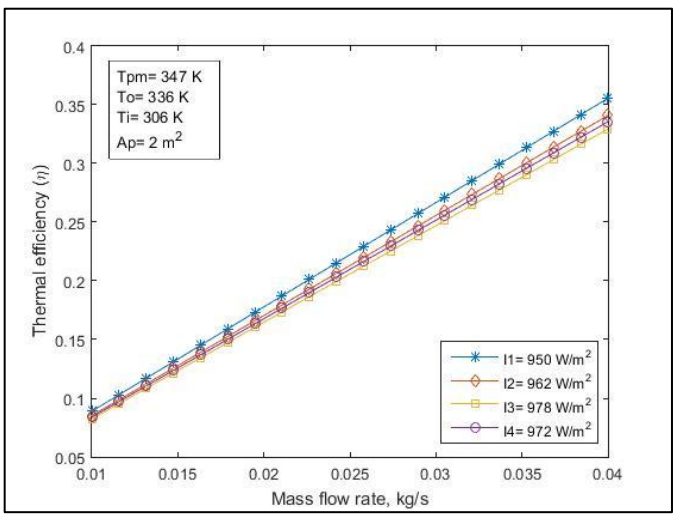


**Fig. 7.** Variation of thermal efficiency vs mass flow rate for different solar radiation.

Fig. 8. illustrates the variation of convective heat transfer coefficient for different ambient temperatures against mass flow rate. From the figure, it has been observed that the nature of graph is linear. It means that as '$h$' increases as '$m$ ' increases. Also, higher ambient temperatures contribute to higher '$h$' which is evident from the graph.

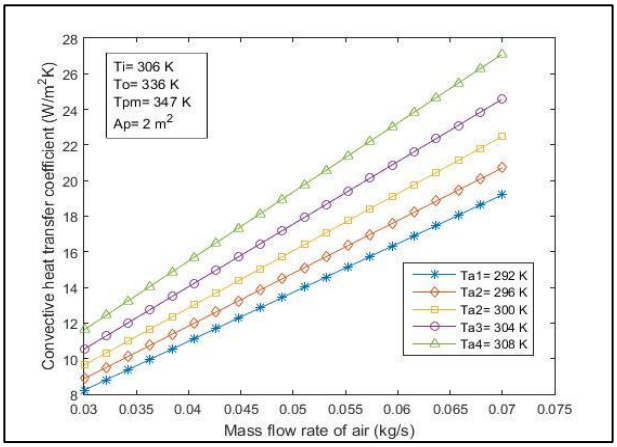


**Fig. 8.** Variation of convective heat transfer coefficient vs mass flow rate for different ambient temperatures.

To mitigate side and bottom losses from the SAH, the addition of suitable insulation materials with appropriate thickness proves effective. In this study, three different insulating materials, namely thermocol (k= 0.050 W/mK), glass wool (k= 0.031 W/mK), and bubble wrap (k= 0.038 W/mK), were utilized to evaluate their impact on thermal performance. Fig. 9. illustrates the relationship between insulation thickness (ranging from 0.002 m to 0.008 m) and side and bottom loss coefficients for the various insulating materials. The findings demonstrate that as insulation thickness increases, the side and bottom loss coefficients decrease, with the lowest values observed at an insulation thickness of 0.008 m. However, it should be noted that higher insulation thickness also translates to increased production costs. Hence, a careful balance is necessary to determine an optimal insulation thickness, considering both thermal performance and cost considerations.

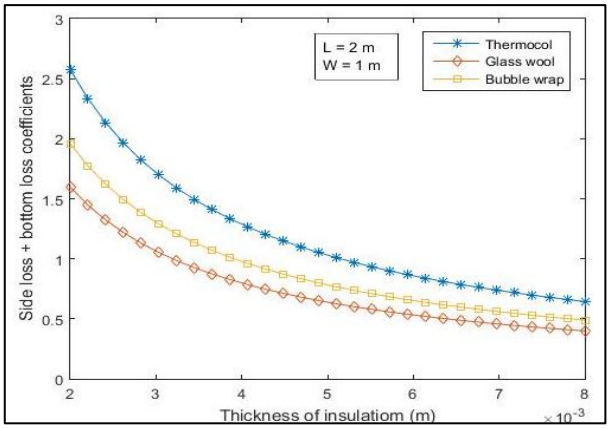


**Fig. 9.** Variation of side loss + bottom loss coefficients vs thickness of insulation for various insulating materials

As seen from Eqns. (2) and (3), increasing the collector efficiency factor can rise the overall heat gain. Additionally, the collector efficiency factor '$F$' is impacted by the overall

heat loss coefficient, which in turn depends on the thickness of the insulation. Fig. 10. displays the fluctuation of '*F*' with $t_i$ (0.002 m-0.008 m) for various insulating materials. Clearly, the '*F'* rises as insulation thickness does. The graph clearly shows that *F* for glass wool and bubble wrap is way greater than that of thermocol. At $t_i$= 0.004 m-0.0045 m, *F* for bubble wrap and glass cover are almost similar.

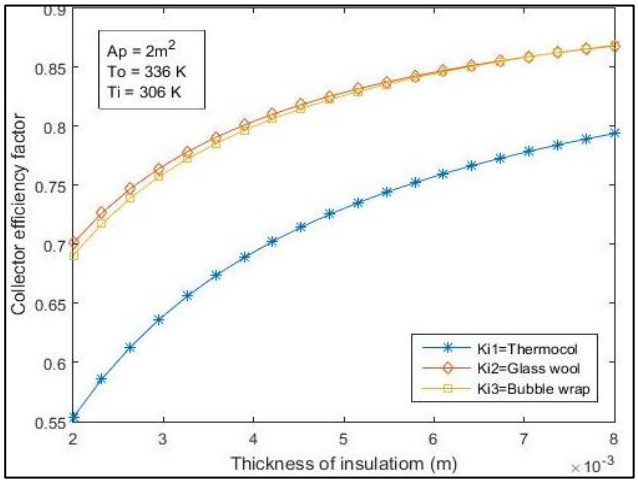


**Fig. 10**. Variation collector efficiency factor vs thickness of insulation for different insulating materials.

The variation of collector thermal energy gain or overall heat gain against overall heat loss coefficient can be seen from the Fig.11. for different absorber plate areas. It is seen that as the coefficient of heat loss increases the energy gain decreases and after a loss coefficient of about 51 W/m$^2$K the energy gain reaches a similar minimum value for all the absorber plate areas. So, the overall heat gain also depends on the thermal conductivity of the material and thickness of insulation as it effects the overall heat loss coefficient.

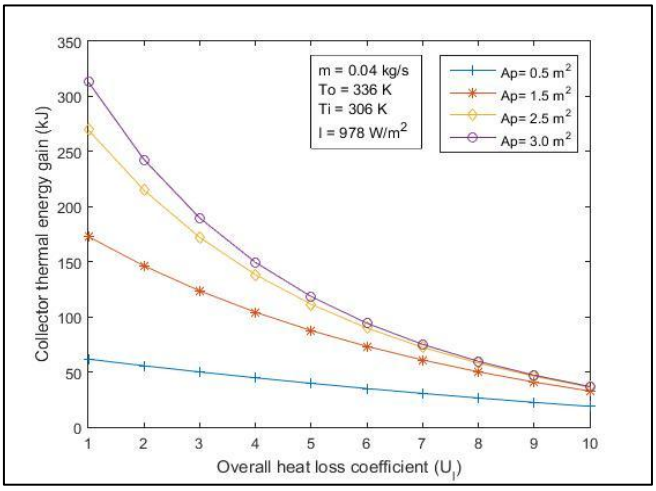


**Fig. 11.** Variation of collector thermal energy gain vs overall heat loss coefficient for different absorber plate area.

## 4 Conclusion

Improving the thermal efficiency of solar-powered air heaters is a challenging pursuit. An important point to note is that, that the effectiveness of heat transfers between the fluid and the solar absorber plate is significantly influenced by the degree of heat transfer coefficient. Also, the utilization of thermal storage devices during off-peak hours has not been extensively explored. Therefore, there is a need to focus on effective methods for conserving and utilizing thermal energy. This study utilizes MATLAB software to examine the influence of different performance parameters on the thermal performance of solar air heaters. The parameters investigated include absorber plate area, mass flow rate, thickness of insulation, and convective heat transfer coefficient. Three different insulating materials, namely thermocol, glasswool, and bubble wrap, are employed in this study. The results provide the following conclusions:

- As the area of the absorber plate rises, the thermal effectiveness of the air heater powered by the sun falls.
- The thermal efficiency increases with an increase in mass flow rate, as evident from the graphical representation.
- The coefficient of heat transfer and mass flow rate have a linear relationship, meaning that as the mass flow rate rises, so does the heat transfer coefficient.
- Increasing the thickness of insulation leads to a reduction in losses from the side and bottom of the absorber plate.
- The collector efficiency factor for glasswool and bubble wrap exhibits similar values within the insulation thickness range of 0.004-0.0045 m, whereas it is significantly lower for thermocol.
- The heat loss coefficient increases as the energy gain decreases.

The scope for future work includes designing and fabricating the proposed solar air heater (SAH), conducting experimental analysis on the fabricated SAH, and comparing the experimental results with numerical simulations to assess the system's efficacy and productivity.

## Statements and declarations

The authors declare no competing interests. They confirm that they have no financial or non-financial interests in the materials discussed in this paper.

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