CFD Modelling and Thermal Performance Evaluation of a Double-Pass Solar Air Collector

Abdullaev Otabek[1], *Fayzullaev* Sherali[1], *Ibragimova* Zaytuna[2], *Shokirov* Sardor[3*], *Murodova* Dildora[4], *Akramova* Surayyo[5]

[1]Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Tashkent, Uzbekistan
[2]"Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University, Tashkent, Uzbekistan
[3]Bukhara State University, Bukhara, Uzbekistan
[4]Asia International University, Bukhara, Uzbekistan
[5]Bukhara State Pedagogical Institute, Bukhara, Uzbekistan

Abstract. This paper conducts a numerical analysis based on computational fluid dynamics (CFD) of a double-pass solar air collector with the help of COMSOL Multiphysics. The collector will have a perforated corrugated absorbent plate and this allows increased turbulence and increased convective heat transfer. The five inlet holes are located below the absorber and air is admitted invrino with the vertical orientation followed by passing through the overheated absorber surface and finally out through the outlet. The simulation is provided with varying values of solar radiation that reflect the actual daytime spatial values which varies between 552-855 W/m^2 of solar irradiance. The influence of the velocity of inlet air (0.5 m/s) and inlet temperature (298.15 K) on the thermal performance is considered. Important performance factors including temperature distribution, convective heat transfer coefficient, useful energy gain and the overall thermal efficiency are numerically calculated. A double-pass design improved the outlet air temperature by 10-14 ^{0}C, the convective heat transfer coefficient by 22-31 %, and thermal efficiency by 18.4 % over a conventional single-pass collector. The findings indicate that the double-pass system is highly effective in thermal performance than the conventional single-pass systems especially when exposed to changing solar conditions.

1 Introduction

Solar thermal applications using solar air heaters (SAH) are mainly attributable to the ease of implementation in many systems such as ventilation preheating, crop drying, and space heating due to their low cost and well-suited design [1, 2]. Improving the thermal efficiency of SAHs still remains a first priority especially in cases where the solar radiation varies. One of the most effective performances enhancing arrangements is perhaps the double-pass

* Corresponding author: s.i.shokirov@buxdu.uz

configuration which enhances convection of heat at the absorber surface and increases the span of time taken by air to travel [3, 4].

Also, corrugated or perforated absorber plates have found application in air mixing, generation of turbulence and enhancement of convective heat transfer with no significant consequence on increased pressure loss [5, 6]. One way to improve the general thermal performance of solar air collectors is to double-pass the air path with an absorber surface being corrugated or perforated [7].

To be able to optimise several design parameters such as absorber geometry, airflow setup and time variable boundary conditions, latest advancements in Computational Fluid Dynamics (CFD) have been able to model thermal and fluid behaviour in SAHs with high precision [8, 10]. As a method capable of providing detailed resolution on the temperature distribution, convective heat transfer coefficients and energy gain over a controlled environment, CFD modelling can be considered a reliable alternative to experimental evaluation [11].

Although there has been a lot of development in numerical and experimental research, very little research has been done on the application of double-pass SACs with perforated corrugated absorbers when subjected to transient solar irradiation. The available models largely presuppose the constancy of conditions or single-pass models, which is why there is a definite gap in research that the proposed work seeks to fill.

In this sense, the present work also employs an alternative method to simulate the solar air collector by employing COMSOL Multiphysics that numerically models a perforated-corrugated absorber plate of a solar air collector in the form of a double-pass collector. Better fluid mix is achieved with vertical and horizontal flow paths since air moves up to the heating plane once it enters through five inlet slots below the absorber. The model evaluates variable solar to irradiance, temperature distribution, conduction heat transfer, useful energy gain and the collector efficiency. These findings help to develop superior SAHs that would suit a variety of thermal processes and varying solar.

This study is novel in the sense that it has modelled a transient double-pass collector with five vertically aligned inlet jets interacting with a perforated-corrugated absorber under realistic diurnal solar radiation and has not been addressed before through literature.

2 Materials and methods

2.1 Geometry configuration

It is supposed that the double-pass design of the solar air heater, which has been considered in this study, enhances heat transfer as a result of prolonged contact time of the air and interaction with surfaces. The collector consists of a rectangular shape structure with dimensions of 0.7 m length, 0.5 m width and 0.2 m high. The central features of the system are a transparent glass cover, a perforated, corrugated absorber plate, an air plenum under the absorber, and thermally insulated side and bottom walls.

There are five circles inlet holes with a diameter of 0.02 meters on the bottom surface below the absorber plate which admit ambient air to enter the system. These are the first and the second passes respectively, in that the air is flowed vertically upward through the absorber, along the perforated surface, into the main heating channel positioned above the absorber. This two-path describes an enhancement of convective heat transfer, ensuring a better contact with the heated surface and promoting turbulent mixing.

To ensure the high solar absorptivity, the aluminium absorber with an aluminium black-coat is used. It can be provided with the maximum solar irradiance and minimum convective and radiative losses due to the transparent surface of glass covering the top of the enclosure. The side and the rear walls are insulated with polyurethane foam insulation commonly used; it has a low thermal conductivity which decreases loses to the environment of thermal energy. The absorber and the air stream, which leaves the system through a horizontal outlet slot close to the top of the rear wall, can exchange heat and absorb solar energy efficiently thanks to this geometric arrangement.

2.2 Finite element solver

The Finite Element Method (FEM) in COMSOL Multiphysics was used to perform the numerical simulation of the double-pass solar air collector. To accurately resolve complex flow and heat transfer behaviour, particularly near the absorber plate and inlet/outlet regions, the computational domain representing the 3D geometry of the collector was discretized using a non-uniform unstructured mesh made up of multiple element types [12].
To guarantee sufficient resolution of thermal and velocity gradients, a physics-controlled meshing technique was used, honing the mesh close to walls, boundaries, and perforated areas. The solver was set up to deal with variable solar input conditions and transient, conjugate heat transfer between the solid absorber and the moving air.
Table 1, which displays the quantity and kinds of elements used in the simulation, provides an overview of the finite element mesh properties. High computational accuracy and a manageable simulation time were guaranteed by the use of 276,183 finite elements in total. The mesh consists of surface elements for wall and interface conditions, prism and pyramid elements close to boundaries, and tetrahedral elements in the bulk region.

Table 1. Finite element solver

Elements type	Number of elements	Tetrahedra	Pyramids	Prisms	Triangles	Edge element
	276183	230603	954	44626	32616	2621

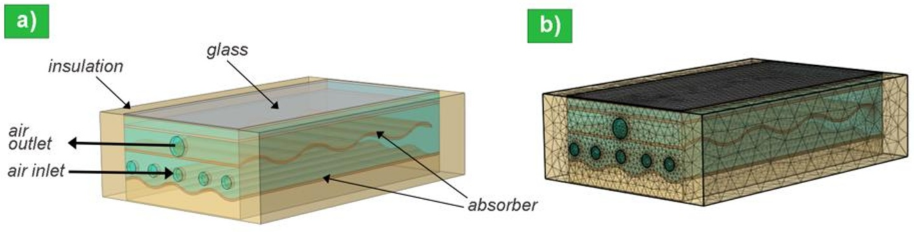

Fig. 1. a) Geometric view of double-pass solar air collector, b) generated mesh size for computational domains.

Figure 1 shows the 3D geometry of the solar air heater along with the generated mesh, highlighting the refined regions around the perforated absorber plate and the fluid-solid interfaces.
The CFD simulation was carried out in a transient mode to ensure that the hourly variation is captured between 09:00 -16:00 so that the dynamic thermal behaviour can be properly predicted.

2.3 Boundary Conditions

The top glazing was subjected to a time-dependent solar heat flux of 552-855 W/m^2. h = 12 W/m^{2}K was used to model external natural convection and surface to ambient radiation was used to compute radiative losses with emissivity 0.9.

3 Equations and mathematics

3.1. For Heat Transfer in Solids

The following equation is used to solve the Heat Transfer in Solids Interface [13].

$$\rho C_p \left(\frac{\partial \mathrm{T}}{\partial t} + \boldsymbol{u}_{trans} \cdot \nabla \mathrm{T}\right) + \nabla \cdot (\boldsymbol{q} + \boldsymbol{q}_r) = -\alpha \mathrm{T}{:}\frac{dS}{dt} Q \tag{1}$$

Terms whose derivatives are time-dependent become zero in a steady-state issue, and the temperature does not change over time.
The first term on the right in equation 1 is thermoelastic damping, where consideration is made of thermoelastic effects in materials [14]:

$$Q_{ted} = -\alpha T{:}\frac{dS}{dt} \tag{2}$$

According to the time derivative part of material and spatial frames, it must be mentioned that the d/dt operator is the material derivative.

3.2. For Heat Transfer in Fluids

The Heat Transfer in Fluids Interface solves for the following equation [15]:

$$\rho \mathrm{Cp} \left(\frac{\partial \mathrm{T}}{\partial t} u \cdot \nabla \mathrm{T}\right) + \nabla \cdot (q + q_r) = \alpha_p \mathrm{T} \left(\frac{dp}{dt} + u \cdot \nabla_p\right) + \tau{:}\nabla u + Q \tag{3}$$

the Cauchy stress tensor, σ, is split into static and deviatoric parts as in:

$$\sigma = -pI + \tau \tag{4}$$

for ideal gases, the thermal expansion coefficient takes the simpler form $\alpha_p = 1/T$

$$\alpha_P = \frac{1\partial\rho}{\rho\partial T} \tag{5}$$

The expressions that involve time derivatives disappear in a steady-state issue, and the temperature is an unchanging quantity with time. On the right hand side of the equation 12 there are heating under adiabatic compression and certain thermoacoustic effects in the first term in the work done by pressure variations. It is usually small when dealing with flows that have low Mach numbers.

$$Q_P = \alpha_P \mathrm{T} \left(\frac{dp}{dt} + u \cdot \nabla_p\right) \tag{6}$$

The second term represents viscous dissipation in the fluid:

$$Q_{vd} = \tau{:}\nabla u \tag{7}$$

4 Results and discussion

The main conclusions of the numerical study of the double-pass solar air heater are presented in this section. These conclusions include the examination of the temperature distribution, the convective heat transfer coefficient, the useful energy gain, and the collector efficiency

 https://doi.org/10.1051/e3sconf/202669201004

under conditions of variable solar radiation. Through transient simulations conducted over an 8-hour daytime period with solar irradiance ranging from 552 W/m² to 855 W/m², the results were obtained using COMSOL Multiphysics.

The surface temperature distribution inside the double-pass solar air collector is shown in Figure 2 at hourly intervals between 9:00 and 16:00. This shows the transient thermal behavior under changing solar irradiance during the day. The temperature contours reveal clearly the variation of heat transfer and absorption of solar energy with time.

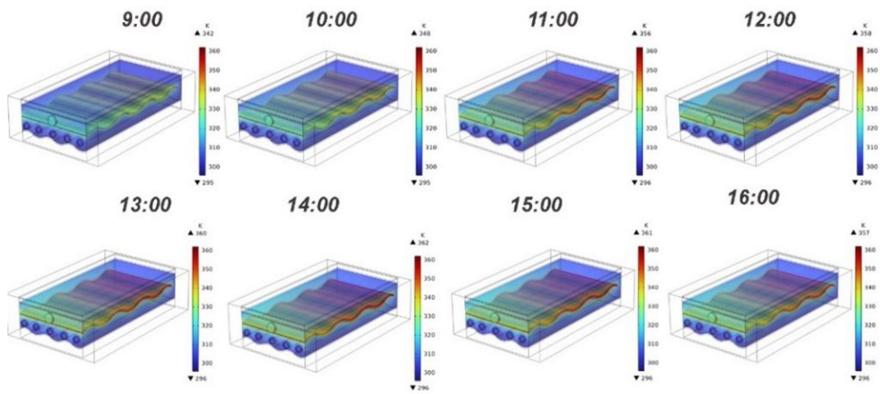

Fig. 2. Surface temperature distribution of Double-Pass Solar Air Collector.

During the early hours of the day (09:00 10:00), the plate aims at absorbing the heat, and the surface temperatures of the absorber plate rise to approximately 296 K to 330 K. The thermal distribution is more apparent in the daytime between 11:00 and 13:00 as the solar irradiance rises and highest surface temperatures in the area of the absorber are above 360 K. The red and orange zones are the areas on the absorber plate that accumulate heat the most since it is in the center of the plate and receives direct solar radiation.

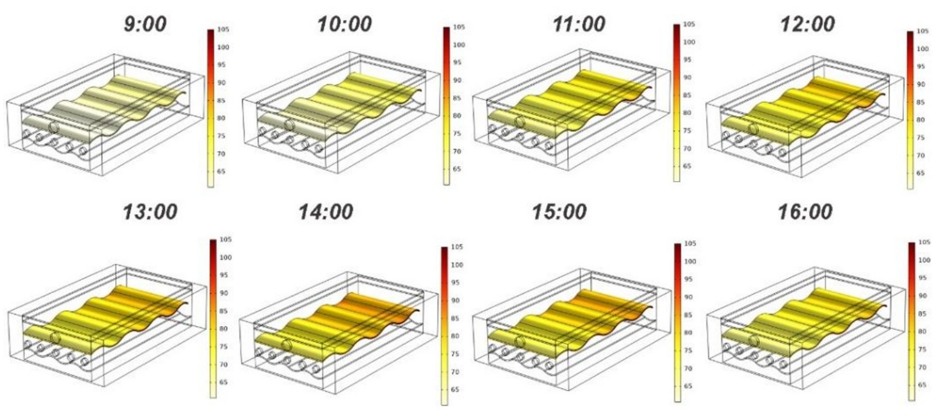

Fig. 3. Absorber surface temperature distribution of Double-Pass Solar Air Collector.

Figure 3 illustrates the distribution of the temperature of the absorber surface of the double-pass solar air collector at 9:00 and 16:00. The data showed that surface temperature rose steadily with time, reaching highs of approximately 105 o C on the days between 12:00 and 14:00, when the solar irradiance was highest. The localized temperature variations by the corrugated absorber geometry enhance convective heat transfer. The thermostats of the absorber ensure that the temperatures are kept above 80 C even at late afternoon that shows that the absorber is efficient in terms of thermal performance and retention of energy. The uniform heating pattern is a testament to the the efficiency of the double-pass design to exploit the solar energy.

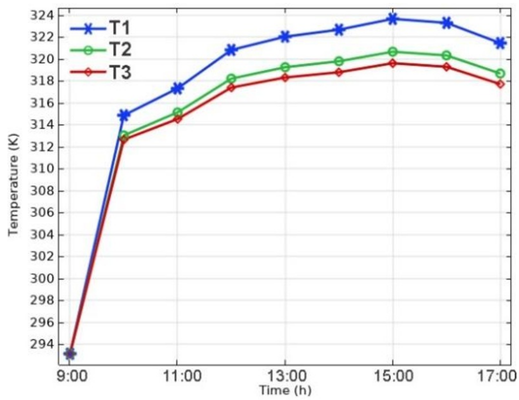

Fig. 4. Temperature variation of air at three different locations.

Figure 4 illustrates the change in temperature of air at three different points (T1, T2 and T3) within the solar air collector equipped with two passes during the day. Between 9:00 and 11:00, there is a rapid rise in the temperature in line with the solar irradiance. The highest temperatures are observed at 14:00, and the temperature of T1 (the nearest to the absorber) is about 324 K, and T2 and T3 are 320 K and 318 K, respectively. After 15:00 there is a slight drop because of the reduction in solar input. The flow of air and efficient heat transfer between the three places by the collector are verified by the consistent temperature gradient.

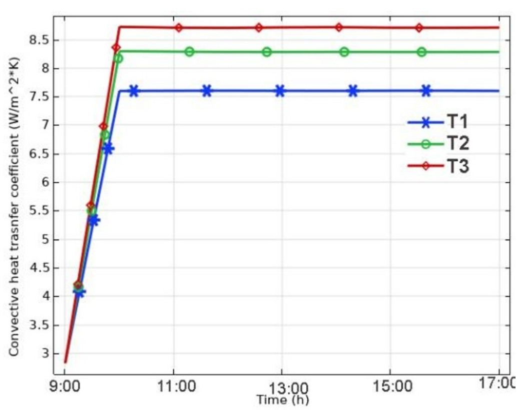

Fig. 5. Convective heat trasnfer coefficients at three different locations.

Fig. 5 demonstrates the convective heat transfer coefficients of a Double-Pass Solar Air Collector at three different times (T1, T2 and T3). The coefficients increase rapidly at the

 https://doi.org/10.1051/e3sconf/202669201004

beginning of the morning and then level off around 10:00 AM. The maximum ratio of the heat transfer coefficient (~8.5 W/m 2 K) belongs to T 3, then T 2 and T 1. After stabilization the values basically remain constant throughout the day, and it shows that the system has steady thermal performance. T3 has increased heat transfer coefficients because of the enhanced mixing of air and increased time of contact with thermal in the top pass where the recirculated warm air is collected. Besides, the doubled geometry provides the repeated contact with the absorber surface.

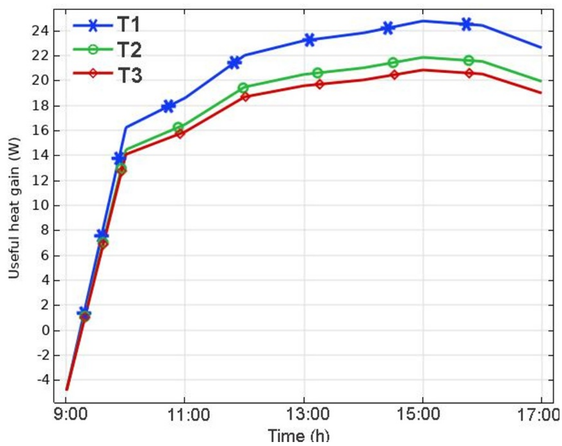

Fig. 6. Useful heat gains at three different locations.

Fig. 6 demonstrates the variation of useful heat gain along the Double-Pass Solar Air Collector at three various points (T1, T2 and T3) throughout the day. The gain of useful heat increases rapidly as the intensity of the sun radiation in the morning increases and reaches a peak between 13:00 and 15:00. This peak period is followed by a slight reduction in the heat gain in the late afternoon. Point T1 will experience the highest heat gain then T2 and 3. This variation is caused by airflow path and temperature distribution within the collector with the smaller areas (T1) capturing more heat. The trend reveals a conversion of the sun energy in the hottest hours of the day with recognizable differences, making the collector very efficient in this regard.

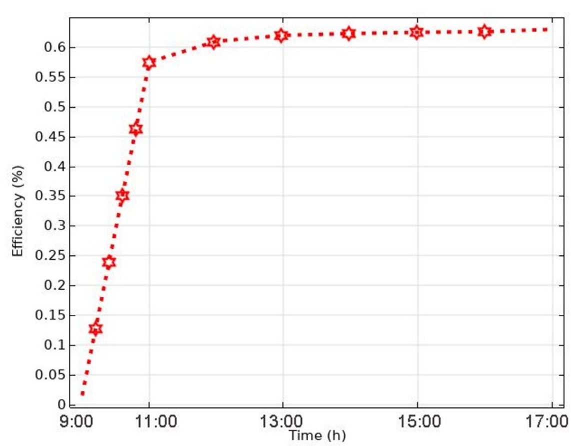

Fig. 7. Efficiency of Double-Pass Solar Air Collector.

The Double-Pass Solar Air Collector's efficiency variation over time is shown in Fig. 7. As solar radiation intensifies in the morning, the efficiency rises quickly, reaching about 0.6% by 11:00 AM. Following this, the efficiency levels out and stays relatively steady throughout the remainder of the day. This pattern suggests that the collector performs best during the midday hours when solar intensity is at its highest, maintaining a steady efficiency under steady-state circumstances.

Typical single-pass collectors exhibit 25–42% lower thermal efficiency under similar conditions [13]. The proposed design provides up to 18% improvement.

Conclusion

This paper is the numerical analysis with CFD modeling of a simplified computational model of the thermal performance of a double-pass solar air collector with a perforated corrugated absorber panel, using COMSOL Multiphysics. The results indicate that the proposed design is effective in promoting heat convection and turbulence in airflow in the system. Workable solar radiation profiles were integrated in order to indicate that the collector produces a regular thermal performance throughout the entire day producing significant improvement of useful thermal gain and convective heat transfer coefficients.

Since a double-pass system is confirmed in terms of optimizing heat absorption, distribution of temperature, heat transfer coefficients, and efficiency of energy absorption in different locations of the collector demonstrate the spatial distribution of its thermal performance. Also, the efficiency of the system grew rapidly early in the morning and stabilized and became nearly constant during the most intense solar moments.

Comparatively, the double-pass solar air collector having perforated corrugated absorber offers a higher thermal efficiency in general and therefore is a promising solution to effective solar air heating processes. Such findings contribute to the further refinement and advancement of state-of-the-art solar thermal systems to be used in environmental-friendly energy consumption.

References

1. K. S. Ong, Thermal performance of solar air heaters: Mathematical model and solution procedure, Solar Energy, **55**, no. 2, pp. 93–109, (1995). doi: 10.1016/0038-092X(95)00021-I.
2. A. K. Hegde, Raghuvir Pai, and K. V. Karanth, Performance augmentation of solar air heaters: A comprehensive analysis, Solar Energy, **253**, pp. 527–553, (2023). doi: 10.1016/j.solener.2023.01.031.
3. C.-D. Ho, H. Chang, C.-F. Hsiao, and Y.-C. Lin, Optimizing Thermal Efficiencies of Double-Pass Cross-Corrugated Solar Air Heaters on Various Configurations with External Recycling, Energies, **14**, no. 13, p. 4019, (2021). doi: 10.3390/en14134019.
4. C.-D. Ho, H. Chang, C.-F. Hsiao, and C.-C. Huang, Device Performance Improvement of Recycling Double-Pass Cross-Corrugated Solar Air Collectors, Energies, **11**, no. 2, p. 338, (2018). doi: 10.3390/en11020338.
5. C. Choudhury and H. P. Garg, Design analysis of corrugated and flat plate solar air heaters, Renewable Energy, **1**, no. 5–6, pp. 595–607, (1991). doi: 10.1016/0960-1481(91)90003-8.

6. J.S. Akhatov, N.I. Juraboev, K.S. Akhmadov, Enhancing Thermal Performance of Solar Parabolic Through Collector by using Corrugated Absorber Tube, presented at the International Conference on Thermal Engineering, (2024). [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85199134634&partnerID=40&md5=ad4aa6930c6b7dc82468dea9b9be895e
7. H. Zhang et al., Mathematical modeling and performance analysis of a solar air collector with slit-perforated corrugated plate, Solar Energy, **167**, pp. 147–157, (2018). doi: 10.1016/j.solener.2018.04.003.
8. S. P. Shetty, N. Madhwesh, and K. Vasudeva Karanth, Numerical analysis of a solar air heater with circular perforated absorber plate, Solar Energy, **215**, pp. 416–433, (2021). doi: 10.1016/j.solener.2020.12.053.
9. V. Madadi Avargani, H. Abdlla Maarof, and S. Zendehboudi, Multiphysics CFD modeling to assess performance of a perforated multi-plate indirect solar dryer with a V-corrugated absorber surface, Applied Thermal Engineering, **227**, p. 120387, (2023). doi: 10.1016/j.applthermaleng.2023.120387.
10. G. Boussouar, B. Rostane, K. Aliane, D. Ravi, M. J. Gęca, and A. Gola, Study of the Thermal Performance of Solar Air Collectors with and without Perforated Baffles, Energies, **17**, no. 15, p. 3812, (2024). doi: 10.3390/en17153812.
11. H. Kidane, I. Farkas, and J. Buzás, Role of computational fluid dynamics in solar air heating: a comprehensive overview of applications, benefits, and future directions, J Therm Anal Calorim, (2025). doi: 10.1007/s10973-025-14261-1.
12. Juraboev N.I., Akhmadov Kh.S., Rashidov K.Yu., Sobirov.M.M, Assessing Thermal Performance of Glass-Envelope Absorber Tubes in Solar Parabolic Trough Systems, ICTEA: International Conference on Thermal Engineering, vol. Vol. 1 No. 1 (2024): ICTEA, (2024) [Online]. Available: https://journals.library.torontomu.ca/index.php/ictea/article/view/2379.
13. W.M. Mutar and Y. Alaiwi, Experimental investigation of thermal performance of single pass solar collector using high porosity metal foams, Case Studies in Thermal Engineering, **45**, 102879, (2023). https://doi.org/10.1016/j.csite.2023.102879.