Performance Enhancement of Solar Air Heaters Using Triangular Channels

Sharafutdinova Marvar[1*], *Musayeva* Amina[1], *Jumayeva* Zamira[1], *Xalilov* Bahromjon[1], *Sodiqova* Nigora[1], *Raximova* Lolaxon[1]

[1]Asia International University, Bukhara, Uzbekistan

Abstract. This paper provides a comparative numerical analysis of two solar air heater (SAH) designs: an improved design with internal triangular air flow channels (SAH 2) and a standard flat-plate duct design (SAH 1). The thermal performance of the two systems under varying levels of solar radiation, typical of a typical day, was investigated using computational fluid dynamics (CFD) from COMSOL Multiphysics. Transient behaviour of heat transfer and airflow was modelled using a time-dependent solver over a period of 08:00- 18:00, when solar irradiance varied on an hour-by-hour basis between 180W/m^2 to 1000W/m^2. It was obtained that the overall thermal performance of SAH 2 under all measured parameters has greatly increased when using triangular channels. The outlet temperature and useful heat gain in SAH 2 have been seen to be higher than in SAH 1 and thus peak colony temperatures in excess of 330K and improvement of the thermal efficiency of up to 20.5 can be observed as well. There were increased convective heat transfer coefficients and inter mixing of air flow because of the changes in geometry leading to increased efficiency in the use of solar energy. Although an increase of the pressure drop occurs at moderate levels, these benefits on performance can justify the application of SAH 2 as a potential passive solar heating solution. This paper demonstrates that triangular channel enhancement to the geometry is a valid way of enhancing the effectiveness of solar thermal systems.

1 Introduction

The principal factors that contribute to the rising efforts to achieve a more efficient utilization of renewable energy sources are the growing world energy demand, the rising fuel prices, and environmental damages as a consequence of emission of greenhouse gases [1]. The scarcity and adverse environmental effects of the traditional energy sources have also contributed to the intensive studies that have been conducted on renewable sources of energy like solar energy, wind energy, nuclear energy, biomass energy as well as hydro energy. Solar energy is one of them that has been identified to have a huge potential to supply the world energy needs whilst having minimal effects on the environment [2]. There is a wide variation in solar thermal technologies in term of the use and operational characteristics. As an

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* Corresponding author: turopova.dilobar@gmail.com

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illustration, some systems like solar cooking, solar water heating, and solar space heating are very simple and easily scalable hence viable within the reach of every person to practice [3]. One of the most attractive technologies concerning solar thermal technologies in industry processes, space heating, and agricultural drying is solar air heaters (SAHs), due to their simple design, non-demanding system maintenance, and integration [4]. Nonetheless, there are various drawbacks associated with the conventional flat-plate solar air heaters (SAHs) such as changes in solar energy because of weather, low thermal conductivity of air by itself, pressure losses in the air path, heat energy losses, and high pump energy requirements [5-7]. To overcome this drawback, several passive means of enhancing heat transfer have been utilized which obviously entails incorporation of surface distortions on the absorber plate in the form of baffles, ribs and fins to enhance heat extraction [8-10].

The rationale behind the proposed study is to carry a numerical analysis through the Computational Fluid Dynamics (CFD) analysis to determine whether the addition of triangular channels have any impact on the thermal performance of SAHs. Comparative analyses have been done by simulating SAHs under different conditions compared to their conventional rectangular ducts and to integrate them to the triangular channels. The parameters that are examined include the temperature distribution, velocity profile, pressure drop and thermal efficiency.

2 Materials and method

2.1 Geometry arrangement

This research paper compares two varying set-ups of a flat-plate solar air heater that has been modelled and examined using the Computational Fluid Dynamics (CFD). The design of the two configurations is the same externally with the difference in the channel to defy the air flow inside.

The first model was named Solar Air Heater 1 and is a typical flat-plate solar air heater using a simple rectangular duct. It comprises a transparent glass lid, a flat absorber and a very well insulated rectangle channel through which the air passes through. The front inlet is used where the air is introduced and the rear outlet where it evacuates.

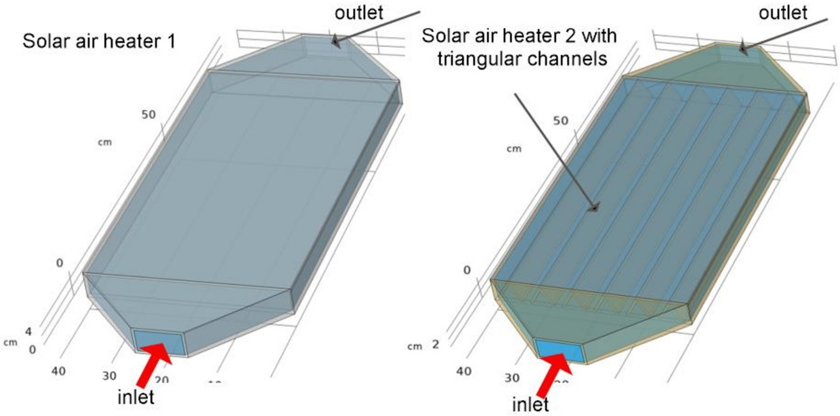

Fig. 1. Schematic view of solar air heaters with and without triangular channels.

The second model, Solar Air Heater 2, introduces a modified duct geometry by integrating triangular channels along the length of the air flow path. These triangular channels are arranged uniformly on the absorber plate and act as passive heat transfer enhancers. The sharp edges and angled surfaces of the triangular inserts disturb the thermal boundary layer and promote turbulent mixing, thereby improving convective heat transfer between the absorber surface and the flowing air.

Both models have the same length (70 cm), width (30 cm), and height (4 cm). The inlet is located at the front face of the duct, and the outlet is positioned at the opposite end. The absorber plate is assumed to be made of high-conductivity material and is subjected to a constant heat flux representing incident solar radiation. The channel walls are thermally insulated to minimize heat loss. Figure 1 provides a visual comparison of the two geometries.

2.2 Finite element solver

The governing equations for fluid flow and heat transfer in the solar air heater models were solved using the Finite Element Method (FEM). The simulations were carried out using a 3D model under steady-state conditions. FEM was chosen due to its accuracy and flexibility in handling complex geometries, especially in modelling internal channel modifications such as the triangular inserts.

Table 1. Finite element solver

	Tetrahedra	Mesh vertices	Triangles	Edge elements	Vertex elements
SAH 1	38419	8096	12822	918	40
SAH 2	921423	223729	-	-	-

Both configurations—Solar Air Heater 1 (SAH 1) and Solar Air Heater 2 (SAH 2)-were discretized with unstructured meshes consisting primarily of tetrahedral elements. A finer mesh was applied near the walls and in the areas around the triangular channels to accurately capture the thermal boundary layer and local flow disturbances. Automatic mesh refinement was applied to ensure numerical stability and convergence.

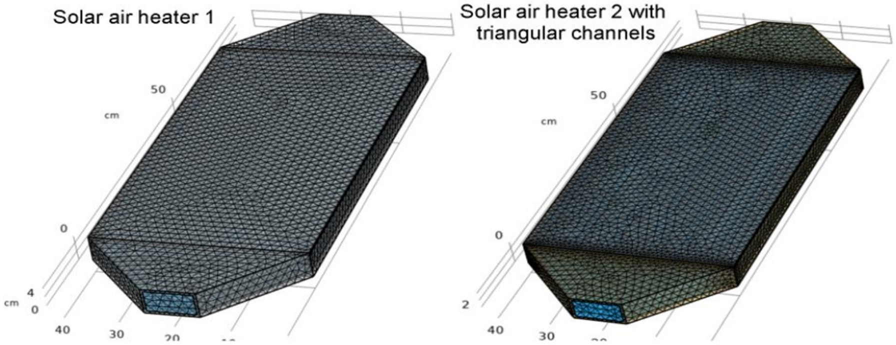

Fig. 2. Generated mesh size for solar air heaters with and without triangular channels.

The mesh characteristics for both models are summarized in Table 1. SAH 2 required significantly more elements due to the presence of internal triangular channels, which increased the geometric complexity and required higher mesh resolution to resolve localized thermal and flow gradients.

The mesh was generated using unstructured tetrahedral elements, with higher resolution applied near the walls and heat transfer surfaces to accurately resolve boundary layer effects. As shown in Figure 2, SAH 2 with triangular channels required a significantly denser mesh compared to the conventional SAH 1 model, due to the increased geometrical complexity introduced by the internal triangular inserts.

3 Transfer of heat in liquids and solids

The Heat Transfer interfaces in COMSOL Multiphysics, which are based on the fundamental principle of energy conservation and well-established formulations reported in the literature [11-12], were used in this study to model heat transfer processes in both solid and fluid domains. The numerical model takes into account both combined convective-conductive heat transfer in the fluid passing through the spiral tube and conductive heat transfer in solid components.

Heat transfer in the solid areas is mainly controlled by thermal conduction in the absorber plate, tube walls, and structural elements. Thermoelastic effects, which depict the interplay between solid materials' mechanical and thermal responses, were taken into account in addition to pure conduction. These effects contribute to the collector's overall thermal behavior by introducing internal heat generation linked to temperature-induced deformation. The analysis was able to concentrate on spatial temperature distributions because temporal temperature variations were disregarded under steady-state conditions.

Both thermal convection brought on by fluid motion and thermal diffusion within the fluid were taken into account when modeling heat transfer in the fluid domain. Pressure-related thermal work, which results from compression and expansion effects within the flow, is also included in the formulation. However, this contribution is still quite small because of the low Mach number regime taken into account in this study. In order to account for the transformation of mechanical energy into heat due to fluid friction and velocity gradients, especially at higher inlet velocities, viscous dissipation was incorporated.

The evaluation of the coupled thermal-fluid behavior under constant operating conditions was made possible by the application of a steady-state assumption for both the solid and fluid domains. The spiral pipe solar collector system's temperature distribution, heat transfer properties, and energy exchange mechanisms can all be thoroughly evaluated thanks to this integrated approach [11-12].

4 Results and discussion

The thermal performance of two solar air heater configurations-SAH 1 (conventional flat-plate duct) and SAH 2 (with internal triangular channels)-was analyzed using a time-dependent CFD simulation. The analysis was conducted over a typical day from 08:00 to 18:00, with hourly varying solar radiation applied as transient surface heat flux on the absorber plate. Key performance parameters such as outlet air temperature, temperature gain, and useful energy gain were evaluated to assess the impact of triangular channel integration.

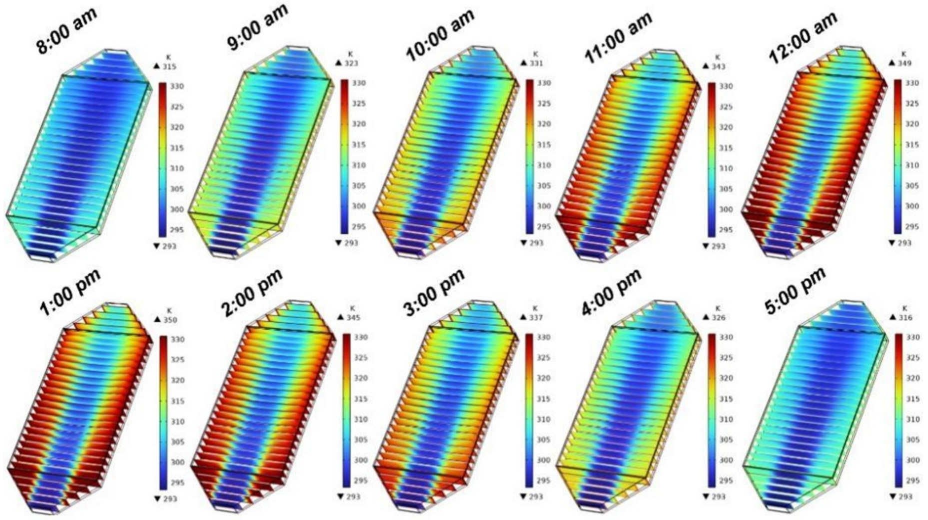

Fig. 3. Temperature distribution of solar air collector 1.

Figure 3 shows the hourly temperature distribution in Solar Air Heater 1 (SAH 1) from 08:00 to 17:00 under variable solar radiation. At low irradiance (08:00–09:00), temperatures remain close to the inlet value. As solar radiation increases, especially between 11:00 and 14:00, temperatures rise significantly, with peak values exceeding 345 K near the outlet. In the late afternoon (after 15:00), temperatures gradually decline, following the drop in solar intensity. The distribution demonstrates a strong dependence of air temperature on solar input and flow direction, with limited mixing across the duct cross-section.

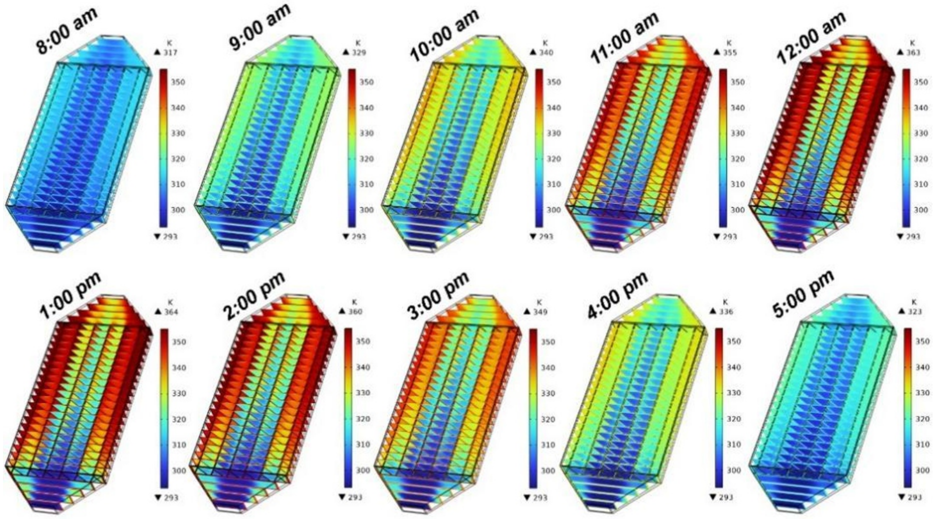

Fig. 4. Temperature distribution of solar air collector 2 with triangular channels.

The temperature distribution in Solar Air Collector 2 with triangular channels between 8:00 and 17:00 is shown in Figure 4. Because there is little solar input in the early hours (08:00–09:00), temperatures stay low. Significant heating takes place as irradiance rises, particularly between 11:00 and 14:00, with peak temperatures surpassing 360 K. Temperatures progressively drop after 15:00 as solar intensity drops. Effective heat transfer along the flow direction is facilitated by the triangular channels.

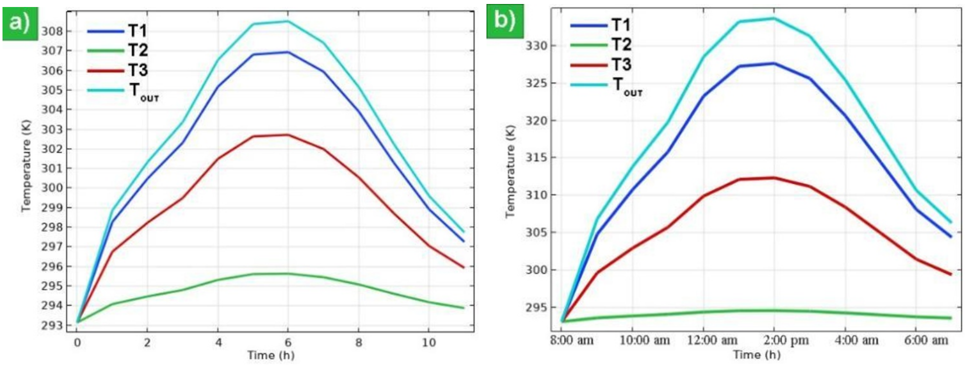

Fig. 5. SAHs' temperature variation at four distinct locations. a) SAH 1, b) SAH 2 with with internal triangular channels.

Figure 5 illustrates the temperature variation at four different points (T1, T2, T3, and T_out) for SAH 1 (a) and SAH 2 with internal triangular channels (b) over the course of a day. In SAH 1, temperatures rise steadily during the heating period, reaching a maximum outlet temperature of around 308 K. In contrast, SAH 2 exhibits a more pronounced temperature increase, with outlet temperatures exceeding 330 K and steeper gradients across all points. This reflects that there is a more effective heat transfer which is due to the increased surface area and turbulence generated by the triangular channels that enhances mixing of airflow and the collection and absorption of solar energy.

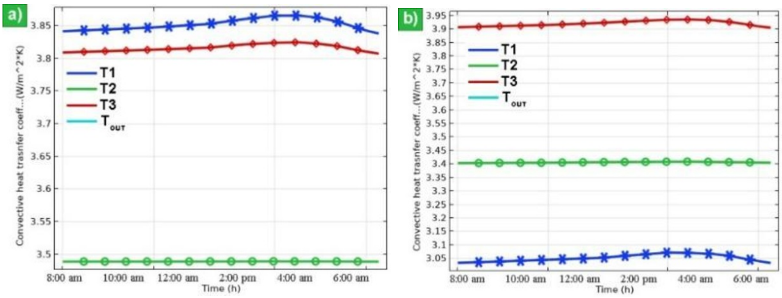

Fig. 6. Change of convective heat transfer coefficients SAHs in four points. a) SAH 1 , b) SAH 2 having internal triangular channels.

In fig. 6, the change of convective heat transfer coefficients (CHTC) at each four positions (T1, T2, T3 and T out) are described at conditions of SAH 1(a) and SAH 2 with internal triangular channels (b). The values of CHTC rise gradually in the presence of peak solar hours in SAH 1 and the maximum values were recorded at the outlet (T_out) to be in the order of 7.88 W/m²·K explicitly in Gunn 2009. The other points vary in a moderate way, since thermal boundary layers tend to grow naturally along the duct.

The CHTC in SAH 2 is more consistent and overall higher at all points in comparison to SAH 1. This improvement comes out specifically at the outlet, with the coefficient near the peak of 8.08 W/m²·K. The enhanced communication is credited to the triangular channels, which can lead to a better flow disturbance and mixing, greater homogeneity and overall efficiency in convective heat transfer in the collector.

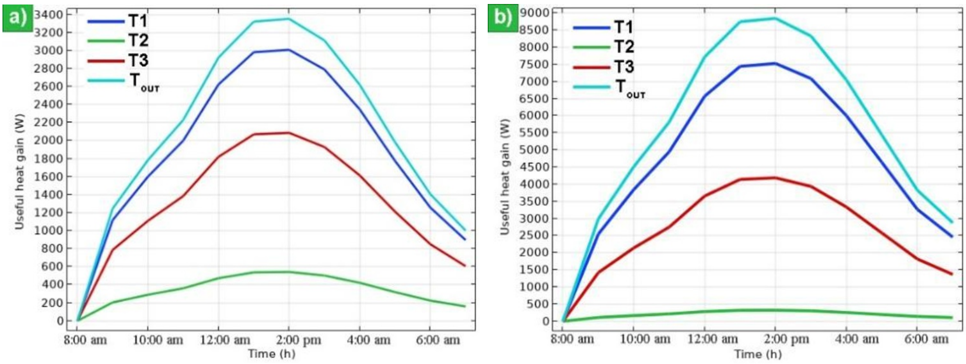

Fig. 7. Analuseement effective of heat by SAHs During four different points. a) SAH1, b) SAH 2 with internal triangular ducts.

Figure 7 demonstrates the useful heat gain at four positions (T1, T2, T3 and T out) in SAH 1 (a) and SAH 2 with internal triangular channels (b) as a time-variant. In SAH 1, the trend of heat gain elevates as the morning progresses, attains the peak in the middle of the day, and the maximum value is found at the outlet. Nevertheless, the overall heat gain is low by virtue of low heat transfer efficiencies.In comparison, SAH 2 shows much better useful heat gain at all locations, but T3, and T out has the highest values of over 9000 W. This is because of increased turbulence and means of increased communication of the surface area causing the triangular channels to enhance a better communication of thermal transfer between the air in flow and the absorber surface. The findings allude to the better energy hoarding abilities of SAH 2 than that of the conventional design.

5 Conclusion

The work here involves a complete numerical evaluation of two-solar air heater (SAH) designs namely; a traditional flat-plate version (SAH 1) and another modified design with internal triangular air channels (SAH 2). The simulation results were obtained under time-varying simulations of COMSOL Multiphysics in terms of the variable solar irradiance conditions which lied in the context of a clear day. The aim was to examine how geometric improvement affected the thermo- performance of solar air heater under transient conditions of operation.

As seen in results, triangular channels enhance the thermal performance of collector significantly when included. SAH 2 was continually more efficient in outlet air temperature, temperature gain and thermal efficiency when compared with the conventional. It is also interesting to note that the maximum outlet temperature in SAH 2 was higher than 330K and the average gain in thermal efficiency was about 20.5 percent compared to the SAH 1. There was an increased convective heat transfer along the duct as a consequence of larger surface area and flow disturbance caused by the triangular geometry resulted in greater transfer of thermal energy. Although the existence of internal structures led to an increase in pressure drop of moderate value, the thermal gains involved therein warrants the use of the structures especially in low-velocity or passive solar heating scenario. The results validate the fact that inclusion of structured internal geometries is a solid strategy towards enhancing the performance of solar thermal systems.

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