CFD analysis of the effect of internal peak angle and mass flow rates on the thermal performance of solar air heater with triangle cross-section

Walid Ben Amara¹, Yashar Aryanfar², Hasan Koten³, Abdallah Bouabidi¹, Mouldi Chrígui¹, Jorge Luis García Alcaraz⁴

¹Mechanical Modeling, Energy and Material (M2EM), National School of Engineering of Gabes (ENIG), University of Gabes, Gabes-Tunisia


³Mechanical Engineering Department, Istanbul Medeniyet University, 34700, Istanbul, Turkey

⁴Higher Institute of Industrial Systems of Gabes (ISSIG), University of Gabes, Gabes-Tunisia


Corresponding author: Hasan Koten, E-mail: hasan.koten@medeniyet.edu.tr

Abstract

A new design of Solar Air Heater (SAH) with triangle cross-section is numerically studied. The thermal performance of SAH is studied at various mass flow rates, inlet air temperatures and solar irradiation intensities. The CFD model is developed using the software “ANSYS Fluent” to study the fluid flow and heat transfer in the solar air heater. 3D discretization is applied to study the thermal performance of solar collector with triangle cross section. Mesh independence is performed in order to choose the adequate mesh. The discrete ordinate radiation model (DOM) and the RNG k-ε turbulence model are used to study the radiative heat transfer and the turbulent flow inside the SAH. Particularly, effects of different internal peak angles (145°, 126°, 100°, 80° and 67.5°) under different solar irradiation intensities (from 620 W/m² to 1081 W/m²) are studied to improve the thermal performance of the SAH. The results show a good agreement between the numerical model and the experimental data with an average error of 6%. The maximum outlet air temperature of the SAH reached 72°C for the geometries with 12 and 16 channels (Internal peak angles of 80° and 67.5°, respectively) under mass flow rate of 0.0264kg/s. The thermal performances of the SAH with 16 and 12 channels are 24.2% higher than standard geometry, respectively for solar irradiation intensity of 1081 W/m². The configuration with internal peak angle of 80° and 12 channels is selected as the optimal with a thermal efficiency of 79%, a low pressure drops compared to geometry with 16 channels and lower costs.

Keywords: Solar air heater, CFD, heat transfer, simulation, Thermal efficiency.

1. Introduction

In recent years, the development of thermal systems based on renewable energies has been booming and has been the subject of many works and achievements [1-3]. The particular case of solar collectors continues to develop, improve and become an important part of our daily life since they constitute a very useful category, and they brought an answer to the energetic transformation destined to the applications in the thermal field. The solar air collector is used in many applications requiring low and moderate temperatures: space heating, drying of agricultural products, drying of wood, and drying of bricks [4-7]. Among those research, T. Koyuncu et al. [8] proposed an experimental investigation on six different flat plate solar collectors to analyze the effect of the number of panes and the shape of the absorber on their efficiency. Findings showed that a collector with single plastic glazing, black painted flat plate absorber and front-pass has a performance of 45.88 %. It is approximately 9% more efficient than a collector with double plastic glazing, black painted flat plate absorber and back-pass). S. Y. Ali et al. [9] performed experimental work on a solar collector by introducing thin rectangular plates oriented parallel to the flow direction and welded to the bottom of the absorber. In their work, the authors compared the case of a double-covered collector to a triple-covered collector through experimental designs. They concluded that
the triple-covered solar collector reduces heat loss to the front and has a higher thermal performance than the double-covered solar collector. According to the literature, the thermal performance of SAH is still relatively low. Despite the various merits of solar air collectors, they require further research to improve their thermal efficiencies [10-30]. The CFD work consists in improving the heat transfer and minimizing the pressure loss by changing the internal peak angle from 67.5° to 145°. Therefore, different configurations of SAH (3, 5, 8, 12 and 16 channels) are studied under different solar irradiation intensities in order to choose the optimal geometry that gives the highest thermal performances and lowest pressure loss.

2. Computational details

2.1 Geometry

The geometry and the different views of the solar air heater with triangle cross-section are shown in Figure 1 and Figure 2. The absorber plate shown in Figure 1(b) comprises 10 copper sheets with dimensions of 1010 mm length, 121.1 mm width and 2 mm height. The sheets were welded together in a triangular shape at an angle of 27° to the flow path and 126° to the other sheet before being mounted in the solar collector. There are rectangular-shaped holes of 100 mm × 170 mm on each copper sheet to make the fluid pass through the channels.

2.2 Governing equations and thermal analysis of SAH

Continuity equations: \( \nabla \cdot (\rho V) = 0 \) (1)

Momentum equations: \( \nabla \cdot (\rho V V) = -\nabla P + \nabla \cdot (\mu (\nabla V - \frac{2}{3} \nabla \cdot V I)) \) (2)

Energy equations: \( \nabla \cdot (\rho V H) = \nabla \cdot (K_f \nabla T) \) (3)

2.3 Grid independence and Boundary conditions

Four meshes are tested to verify the independence of the solution are shown in Figure 3. The different details of mesh such as the number of elements and nodes, the size of elements and the maximum skewness are illustrated in Table 1. The mesh 3 and 4 tends towards the exact solution found by the experimental test (335K) with small difference. The mesh 3 with 572853 elements, is selected as optimal, since it gives the same experimental results, a small storage size and a low calculation time compared to mesh 4.
Table 1: Mesh parameters.

<table>
<thead>
<tr>
<th>Grids</th>
<th>Mesh 1</th>
<th>Mesh 2</th>
<th>Mesh 3</th>
<th>Mesh 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>1276642</td>
<td>1971633</td>
<td>3238611</td>
<td>5969174</td>
</tr>
<tr>
<td>Number of elements</td>
<td>231324</td>
<td>352384</td>
<td>572853</td>
<td>1042422</td>
</tr>
<tr>
<td>Element size of the fluid domain (mm)</td>
<td>18</td>
<td>16</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Element size of the solid domain (mm)</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Max. skewness (%)</td>
<td>82</td>
<td>94</td>
<td>97.8</td>
<td>98.2</td>
</tr>
</tbody>
</table>

Figure 3. Pictorial views of the mesh model with different numbers of grids.

Figure 4. Grid independence analysis for the solar air heater.

The numerical resolution of the adopted mathematical model is conditioned by the initial and boundary conditions applied to the solar air heater are shown in Table 2. The 3-D computational domain is divided into four boundaries in figure 5: inlet, outlet, absorber and insulated walls. At the inlet of the duct, a mass flow rate condition is applied, and velocity values are calculated from the Reynolds number, where the mass flow rate value is 0.0264 kg/s. The sidewalls are considered insulated, and no-slip boundary wall condition is considered.
Table 2: different values of irradiation intensity and ambient temperature.

<table>
<thead>
<tr>
<th>Irradiation (w/m²)</th>
<th>Inlet temperature (K)</th>
<th>Mass flowrate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>620</td>
<td>304.25</td>
<td></td>
</tr>
<tr>
<td>863</td>
<td>305.75</td>
<td></td>
</tr>
<tr>
<td>1015</td>
<td>307.75</td>
<td>0.0264</td>
</tr>
<tr>
<td>1081</td>
<td>310.15</td>
<td></td>
</tr>
<tr>
<td>1076</td>
<td>308.95</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: Boundary conditions applied to the collector.

RNG k-ε turbulence can reasonably predict heat transfer and fluid flow variation and can provide good numerical results in a three-dimensional conduit [32].

3. Validation of CFD model

Figure 6 shows the variation of the numerical results of the Nusselt number as a function of different Reynolds number compared with the standard correlation of the Dittus-Boelter equations below.

Dittus-Boelter equation: \[ Nu = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \] (11)

For different numbers of Reynolds, it notices a good numerical results compared with the correlation of Dittus-Boelter with an average difference do not exceed 6.2%. Figure 7 shows the outlet temperature variation of the collector as a function of solar radiation intensity with a constant mass flow rate of 0.0264 kg/s. The temperature at the collector outlet increases progressively as the radiation intensity increases until it reaches a maximum at noon of about 65 °C when the radiation intensity is very high. All the numerical and experimental values of the outlet temperature for the solar collector are represented in table (3). Also, a good agreement is very remarkable in the figure 3 between the numerical results using ANSYS Fluent code and the experimental results of literature[21], with an error is generally low that does not exceed 6%.

Figure 6. Validation of Numerical modeling with verified correlations.
Table 3: values of the outlet temperature for the solar air heater

<table>
<thead>
<tr>
<th>Irradiation (W/m²)</th>
<th>Experimental results [21]</th>
<th>Numerical results</th>
</tr>
</thead>
<tbody>
<tr>
<td>620</td>
<td>51°C</td>
<td>48°C</td>
</tr>
<tr>
<td>863</td>
<td>55°C</td>
<td>55.5°C</td>
</tr>
<tr>
<td>1015</td>
<td>63°C</td>
<td>61.4°C</td>
</tr>
<tr>
<td>1081</td>
<td>61°C</td>
<td>65°C</td>
</tr>
<tr>
<td>1076</td>
<td>59°C</td>
<td>63°C</td>
</tr>
</tbody>
</table>

Figure 7. Temperature profiles at the outlet of SAH.

4. Results and discussion

4.1. Effect of different mass flow rates

The purpose of this study is to increase the surface of thermal exchange between the absorber plate and the fluid in order to improve the thermal efficiency of SAH.

4.1.1. Velocity distribution

Figure 8 illustrates the velocity contours of a solar air heater. For different mass flow rates, an ambient temperature equal to 310.15 K and solar radiation equal to 1081 W/m². It is noticed a strong acceleration in the middle of the collector and near the heated wall. When the fluid changes direction of flow in a helical way, an important increase of the speed where it can reach 10 m/s when switching from one channel to another. Since the flow rate is low, the low speed is noticeable, especially in figure (d), which does not exceed 4 m/s. Also, it can be seen near the absorbing plate and the external walls that the velocity becomes null because of the non-slip condition.
4.1.2. Velocity fields

Plotted in figure 9, is the distribution of velocities vectors and the solar air heater with different mass flow rates; an ambient temperature was 310.15 K, and radiation intensity was 1081 w/m². As we know, the distribution of vectors is not almost the same for different mass flow rates. The distribution of the vectors varied when the mass flow rate changed from 0.0264 kg/s to 0.018 kg/s. The vectors become null when they contact the walls, and they become very important when the cross-section changes. Also, there are turbulence zones at the exit of each passage that is very noticeable in the zoom of the vectors that slow down the velocity of the fluid.
4.1.3. Pressure contours

Figure 10 shows the relative pressure contours inside the channels for different mass flow rates with the same initial conditions: radiation intensity equal to 1081 w/m², inlet temperature equal to 310.15 K and gauge pressure equal to 0. It can be observed, when the fluid changes the direction of flow in a helical way, a drop in pressure for all the contours where the relative pressure reaches at the exit of the collector -348 Pa for an important mass flow. When the temperature increases, the molecules of the fluid move apart, and the density decreases. Also, by comparing the contours with different mass flows, it is very clear that the pressure loss decreases from 348Pa to 145Pa when the velocity decreases because of the diminution of the frictional forces.

![Pressure contours](image)

Figure 10. Pressure contours with different mass flow rates under solar radiation intensity of 1081 w/m²

4.1.4. Temperature contours

Figure 11 shows the temperature field distribution in the XY plane for a solar radiation intensity equal to 1081 w/m² with different mass flow rates: 0.0264 kg/s, 0.022 kg/s, 0.020 kg/s and 0.018 kg/s. The results show that the air temperature increases progressively from the inlet to the outlet for different mass flow rates. When we have decreased the mass flow rates from 0.0264 kg/s to 0.018 kg/s, we notice that the temperature of the collector output decreases from 342 K to 351.70 K. The two red areas in the contour where the temperature is very high (can reach 375 K) is because the velocity of the fluid is zero.

![Temperature contours](image)

Figure 11. Temperature contours for different mass flow rates.
4.1.5. Temperature profile

Figure 12 shows the solar collector outlet temperature profiles for different mass flow rates as a function of the incident solar radiation intensity. We observe that the difference between the curves is very noticeable when changing the mass flow rate from 0.0264 kg/s to 0.018 kg/s, which gives a very high outlet temperature. When the radiation intensity is high, it reaches 352K at midday for a mass flow equal to 0.018 kg/s.

![Temperature profile](image)

Figure 12. Output temperature profiles of the collector under different mass flow rates.

4.2. Effect of internal peak angle

The purpose is to increase the heat exchange surface between the absorber plate and the fluid in order to maximize the thermal performance of the solar air heater. Figure 13 shows the geometries of solar air heaters with different numbers of channels for the same dimensions: geometry (a) was the reference geometry with 5 channels and an internal peak angle equal to 126°. The geometries (b), (c), (d) and (e) with numbers of channels are equal to 3, 8, 12 and 16, respectively, with internal peak, angles were 145°, 100°, 80° and 67.5° receptivity. All the parameters are shown in table 4.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Numbers of channels</th>
<th>Internal peak angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>5</td>
<td>126°</td>
</tr>
<tr>
<td>(b)</td>
<td>3</td>
<td>145°</td>
</tr>
<tr>
<td>(c)</td>
<td>8</td>
<td>100°</td>
</tr>
<tr>
<td>(d)</td>
<td>12</td>
<td>80°</td>
</tr>
<tr>
<td>(e)</td>
<td>16</td>
<td>67.5°</td>
</tr>
</tbody>
</table>

Table 4. Geometric parameters of the channels.
4.2.1. Velocity distribution

Figure 14 illustrates the velocity contours of a solar air heater with a mass flow rate equal to 0.0264 kg/s, an ambient temperature equal to 310.15 K, and solar radiation equal to 1081 W/m². We notice a strong acceleration in the middle of the collector and near the heated wall for all geometries. In figures (d) and (e), we can see that the velocity can reach 20 m/s when switching from one channel to another, but figure (b) does not exceed 6 m/s because the passage section is very large compared to the other sections.

4.2.2. Velocity fields

The distribution of velocity vectors is not uniform inside the collector, which is represented in figure 15. When the fluid changes flow direction in a helical way, an increase of velocity for all the contours is observed, where the velocity vectors can reach 24 m/s for the geometry with 16 channels (with 67.5°
internal peak angle). Comparing the contours with the same mass flow rates equal to 0.0264kg/s makes it very clear that the velocity of vectors increases when the number of channels increases (the internal peak angle decreases from 145° to 67.5°) due to the decrease of the passage section. Also, there is the presence of vortex zones when the fluid passes from one channel to another.

![Velocity vector contour for all geometries](image)

(a) 5 channels (reference geometry)
(b) 3 channels
(c) 8 channels
(d) 12 channels
(e) 16 channels

Figure 15. Velocity vector contour for all geometries

4.2.3. Pressure contours

Figure 16 shows the pressure distribution inside the SAH for the different geometries under solar irradiation intensity of 1081W/m² and mass flow rate of 0.0264kg/s. The air relative pressure decreases as the internal peak angle changes from 145° to 67.5°, i.e., when the number of channels increases from 3 to 18 channels. According to figure (b), the pressure drop is very low and does not exceed -226Pa is due the air particles do not undergo a great resistance during its passages in the channels with large section. As the number of channels increases, the contact surface between the fluid and the internal walls increases, which causes linear pressure losses (friction) and singular pressure losses. The depression is clearly shown in figure (e), where the pressure drops to -622 Pa in the medium.
Figure 16. Pressure contours with a mass flow rate equal to 0.0264 kg/s and radiation intensity equal to $1081 \text{ W/m}^2$

4.2.4. Temperature distribution

Figure 17 shows the solar air heater's temperature contours for different geometries obtained by CFD simulation, with a mass flow rate equal to 0.0264 kg/s, the inlet temperature is 310.15K, and irradiation intensity is 1081 W/m2. The air temperature increases progressively during the passage inside the SAH for all contours. Also, the red areas in all the figures representing a high temperature reaching 375K are caused by the cancellation of fluid velocity as it enters a closed area. In comparison, the difference in the temperature distribution between the five contours is very noticeable. As shown in figure (b), the air temperature increases slowly and does not exceed 340K at the outlet of the solar air collector, which is almost the same as the outlet temperature of the reference geometry. In figures (c), (d) and (e), the outlet temperature is higher compared to the figure (a) (the reference geometry); they exceed 345K, and it can be observed that the fluid temperature of the collector stays constant for the figures (c), (d) and (e) with 8, 12 and 16 channels respectively.
Figure 17. Temperature contours for all geometries with the same mass flow rates.

Figure 18 shows the solar collector outlet temperature profiles for all geometries as a function of the different solar radiation intensities. It is observed that the difference between the curves is small when the solar flux is low. On the other hand, at noon, when the intensity of solar radiation is very important, the difference becomes remarkable.

Figure 18: The profiles for the outlet temperature of the solar air heater with different solar radiation intensities.

4.2.5 Thermal efficiency variation

Figure 19 shows the variation of thermal efficiency for different configurations under a mass flow of 0.0264 kg/s and different solar irradiation intensities. It is observed that the thermal performances of all configurations increases with the increase in the number of channels from 3 to 16 (reduction of the internal peak angle from 145° to 80°). Comparing the results for all solar irradiation intensities, it is noticed that the thermal efficiency for the configurations with 8, 12 and 16 channels higher than the geometry of Haydari et al. [21]. This is due to a better heat transfer on account of the increased heat transfer surface by decreasing the internal peak angle. In terms of values, the thermal performances of the SAHs with 16,12 and 8 channels are 34.9%, 34.8% and 23% higher than SAH with 5 channels [18] for solar irradiation intensity of 1081 W/m². Furthermore, the maximum efficiency is found for the geometry with internal peak angle of 80° (12 channels) and it reaches 79.8% and the average efficiency is 78% under mass flow rate of 0.0264kg/s. Moreover, it is noticed the geometries with 16 and 12 channels generally give the same thermal efficiencies for solar irradiation intensity varied from 620 W/m² to 1081W/m² under mass
flow rate of 0.0264 kg/s. Table 5 summarizes the thermal efficiencies of different types of solar air collectors. It can be seen that the configuration proposed in this study (with 12 channels) gives a better thermal performance compared to the configurations of the other studies. This is due to the importance of using a V-shaped absorber with internal peak angle of 80° which increases the heat exchange surface.

![Graph showing thermal efficiency of different configurations under different mass flow rates.](image)

Figure 19. Comparative variation of thermal efficiency of different configurations under different mass flow rates.

Table 5. Summary of some studies about different types of solar air heaters.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Type</th>
<th>Dimensions of the collector</th>
<th>Mass flow rate</th>
<th>Thermal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rasham et. [28]</td>
<td>double-pass counter flow SAH with V-grooved absorber plate</td>
<td>2m × 1 m</td>
<td>0.02-0.09 kg/s</td>
<td>40-74%</td>
</tr>
<tr>
<td>El-Sebaii et. [13]</td>
<td>double pass v-corrugated plate solar air heater</td>
<td>1 m × 1 m</td>
<td>0.01-0.06 kg/s</td>
<td>52-66%</td>
</tr>
<tr>
<td>MesgarPour et. [29]</td>
<td>a double pass solar air heater with helical flow path (HFP) with ratio of $\alpha_{1}/\alpha_{2} = 0.8$</td>
<td>1.085m×1.01m</td>
<td>0.016 kg/s</td>
<td>57-86%</td>
</tr>
<tr>
<td>Benli et. [33]</td>
<td>Single-pass SAH with corrugated absorber</td>
<td>0.7 m × 0.7 m</td>
<td>0.02-0.05 kg/s</td>
<td>5-55%</td>
</tr>
<tr>
<td>Debnath et. [34]</td>
<td>Single-pass SAH with Wavy absorber plate.</td>
<td>1.52m × 0.52m</td>
<td>0.0039-0.0118 kg/s</td>
<td>26-38%</td>
</tr>
<tr>
<td>Aissaoui et. [35]</td>
<td>Single-pass SAH with Flat plate black coated (solar intensity varied from 400 to 900 W/m²).</td>
<td>2m × 1 m</td>
<td>0.1324 kg/s</td>
<td>22-40%</td>
</tr>
<tr>
<td>Heydari et. [21]</td>
<td>solar air heater with helical flow path (solar intensity varied from 620 to 1085 W/m²).</td>
<td>1.085m×1.01m</td>
<td>0.0264 kg/s</td>
<td>52-77%</td>
</tr>
<tr>
<td>This study</td>
<td>triangle cross-section SAH with different internal peak angles (solar intensity varied from 620 to 1085 W/m²).</td>
<td>1.085m×1.01m</td>
<td>0.0264 kg/s</td>
<td>54-79.8%</td>
</tr>
</tbody>
</table>

5. Conclusion

In this work, the thermal performance of a solar air heater with triangle cross-section is studied numerically. The numerical model is validated against the experimental data and the average error does not exceed 6%. The effect of different internal peak angles (145°, 126°, 100°, 80° and 67.5°) on the thermal performance of SAH are investigated numerically under different solar irradiation intensities varies from 62 W/m² to 1081 W/m² and mass flow rate of 0.0264 kg/s. The velocity distribution, pressure contours and the air temperature inside the SAH are presented. The maximum air temperature of
SAH reaches 72° for both configurations with internal peak angle of 80° and 67.5°. The thermal efficiency of geometry with 12 channels (internal peak angle of 80°) is 24.2% higher than standard SAH under a mass flow of 0.0264kg/s and solar irradiation intensity of 1081W/m^2. Despite their high thermal performance, the geometries with triangle cross-section are complex which causes a significant pressure loss and needed to improve the geometric parameters in order to minimize pressure drops.

REFERENCES


Paper submitted: 18.09.2022
Paper revised: 20.12.2022
Paper accepted: 26.12.2022