

Numerical Study for Performance Evaluation of Plastic Solar Air Heater with Different Cross-Sectional Configuration

دراسة نظرية لتقييم أداء سخان هواء شمسي بلاستيكي ذو مقاطع مختلفة

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الملخص

في هذا البحث تمت دراسة خمسة مقاطع مختلفة المساحة السطحية للمقطع الذي يدخل منه الهواء للسخان الهوائي الشمسي للمقارنة بينهم من ناحية الكفاءة الحرارية. المقاطع التي تمت دراستها كالأتي (دائري، نصف دائرة مضاف اليه مثلث متساوي الأضلاع، نصف دائرة، نصف دائرة مقطوع منه مثلث متساوي الأضلاع وشكل هلال) و جميع الأشكال لها نفس مساحة مقطع السطح الماص لأشعة الشمس. وتمت الأختبارات ببرنامج أنسز 14.0 وعندما درسنا تغير السرعة من 0,25 الي 2,0 (متر/ثانية) وكانت النتائج كالأتي أن الشكل الدائري للسخانات الهوائية الشمسية هي الأحسن من ناحية الكفاءة الحرارية بقيمة 51,79%. وعند ثبوت الأشعاع الشمسي عند 850 (وات/متر²) وعند عمل الأختبار الثاني وذلك بتغير قيمة الأشعاع الشمسي من 400 الى 1200 (وات/متر²) مع ثبوت قيمة سرعة الهواء عند 1,0 (متر/ثانية) كانت النتائج كالأتي أن الشكل الدائري هو الأعلى كفاءة حرارية بقيمة 35,5%.

ABSTRACT

In this research, a numerical investigation was performed on five solar air heaters with different cross-sectional shape to find the best configuration relevant to thermal performance. The selected tested shapes in this study were (circular, semi-circular, half-circle plus isosceles triangle, half circle-negative isosceles triangle shape and crescent shape) and all tested shapes had the same absorber surface area. The effect of two parameter (velocity and solar radiation intensity) on thermal performance of solar air heater were studied numerically by ANSYS 14.0. The velocity of air was changed from 0.25 to 2.0 (m.s⁻¹). Results indicated that the highest efficiencies were accomplished for the circular configuration and reached to about 51.79% at solar radiation intensity 850 (W.m⁻²). The solar radiation intensity was changed from 400 to 1200 (W.m⁻²). Results indicated that the highest efficiencies were accomplished for the circular configuration and reached to about 35.51% at air velocity 1.0 (m.s⁻¹).

1. Introduction

Solar air heaters (SAHs) , represent the primary component of solar energy usage systems. (SAHs) are used to convert the solar energy to thermal energy by increasing the temperature of air flow through the (SAHs).To obtain heated air we use a combustion of fuels, which have productions of (CO₂, SO₂, NO_x) gases which cause air pollution, rain acid and damage the environment therefore all world wards to renewable energy to reduce the air pollution. The biggest source of renewable energy is the sun. The outlet temperature is used in several industrial applications [1, 2, 3], like crop drying, textile dyeing, building heating and water desalination.

1.1 Solar air heater collector's types:

- Unglazed solar air collectors or (transpired solar collectors) used primarily to heat ambient air in commercial, industrial, agriculture and process applications.

The term "unglazed air collectors" refers to a solar air heating system that consists of an absorber without any glass or glazing over top. Unglazed solar air collectors usually wall-mounted to capture the lower sun angle in the winter heating months as well as sun reflection off the snow and achieve their optimum performance.

- Glazed solar air collectors recirculating types that are usually used for space heating.

Glazed air collectors, functioning in a similar manner as a conventional forced air furnace, systems provide heat by recirculating conditioned building air through solar collector. Glazed air collectors are a simple and effective collector can be made for a variety of air conditioning or process applications, the air is ducted to the building space or to the process area where, the heated air is used for space heating or process heating needs.

A simple solar air collector consists of an absorber material sometimes having a selective surface to capture radiation from the sun and transfers this thermal energy to air.

The SAHs, have many advantages, the simple design component, no emissions, low costs to build it, longer maintenance and can built over any roof. In another side SAHs have low thermal efficiency and this is due to heat loss through the cover.

There are several studies to improve the thermal efficiency of solar air heater and all of them refer to increasing the heat transfer coefficient [4, 5] by changing the flow air through SAHs from laminar to turbulent regime by using fins or turbulators which attached over the absorber surface. Ho et al. [6] found experimentally and theoretically that

heat transfer is improved when fins were attached over the absorber surface and they found that heat transfer improve by attaching fins and thermal efficiency were increased by increasing Reynolds number (Re) .Yadav and Thapak [7] used another way to make the flow turbulent by attaching ribs on the absorber surface and they found that the flow turbulent near the wall increased and improved the heat transfer and increased the thermal efficiency. Sharma et al. [8] used ribs as artificial roughness to improve the heat transfer coefficient and they found that heat transfer improve by attaching ribs on the absorber surface and thermal efficiency were increased by increasing Reynolds number (Re) Yadav and Bhagoria [9] used transverse wire rib roughness and they found that heat transfer improve by this method and thermal efficiency were increased by increasing Reynolds number (Re). Rawat et al. [10] used 60° inclined V- shape ribs and they found that heat transfer improve by increasing Reynolds number (Re).

There was another method to improve the thermal efficiency by using packed bed materials were used as store heat during the day to be reused at night to increase the out let temperature. El Khadraoui et al. [11] used packed bed materials to improve the thermal efficiency they were indicated that the thermal energy which stored during the day used during the night by this ensured increasing the

outlet temperature of SAHs all day. Naphon [12] used numerically method to study the effect of thermal conductivity of porous media packed bed of double- pass SAHs and they found that heat transfer improve by using packed bed method and double- pass SAHs had thermal efficiency better than one pass. Gill et al. [13] fabricated and compare between of pack bed, double glazed and single glazed and they found the results were the efficiency of pack bed is the highest and reached to 71.7%. There was another side it desired to have cheap cost to design the SAHs, many paper had been studied for thermal efficiency with low cost of component. Njomo [14] compared the plastic and glasses cover thermal performance and cost for them. The results found that using plastic cover decrease the cost of designing the SAHs. Janjai et al. [15] also used plastic cover and they concluded that thermal efficiency was increased as the length of SAHs increased till reached to 20 m whiles increasing length more than 20 m there was no notable increase in thermal efficiency. Bansal et al. [16] applied two solar air heaters with low cost absorber materials one with black textile absorber and the other with black PVC foil they found that the thermal efficiency was increase about 18% and the increase of the outlet temperature was about 10 °C. Ahmad [17] designed a solar air heater with cheap plastic cover with air bubbles they found that the thermal efficiency was increase about 12.5% and the increase of the outlet

temperature was about 10 °C. Abdullah and Bassiouny [18] used flexible cylinder type plastic SAH, with circular shape with 0.5 m diameter. They concluded that the outlet temperature increased as the mass flow rate was increased. Abdullah et al. [19] used different cross sectional for solar air heater (circle, semi-circle and half circle-plus isosceles triangle) had same absorber surface area with plastic cover, the thermal performance studied with varied mass flow rate experimentally. They concluded that the highest efficiencies were accomplished for circular shape and reached to about 82.2% at mass flow rate 0.25 (kg.s⁻¹).

To the author's knowledge effect of inlet air velocity and solar radiation intensity on thermal performance of solar air heater with different five cross sectional area were studied numerically.

Different cross sectional shapes were studied were (circle, semi-circle, half circle-plus isosceles triangle, half circle-negative isosceles triangle and crescent shape).

All the SAHs had the same absorber area semi-circle with (diameter D= 0.3 m and length L=20 m), the all shapes had the same plastic cover with emissivity coefficient 0.98 and all of them were studied at same boundary conditions.

2. Numerical Work

A numerical simulating program is used in the current search is ANSYS 14.0, it is used to solve set of equations which describe the processes of momentum, the steady-state equations of heat and mass transfer. The ANSYS 14.0 CFX is based on finite volume techniques to solve these equations. In this technique the region which tested, divided into small sub-regions called control volumes. The equations discretized and solved iteratively for each control volume. As a result, an approximation of the value of each variable at specific points throughout the domain can be obtained. In this way, a full picture obtained of the behavior of the flow. The geometry of the region of interest is then defined. The mesh is then created after importing the mesh into the pre-processor other elements of the simulation including the boundary conditions (inlets, outlets, etc.) and fluid properties were defined. The flow solver was run to produce a file of results that contains the variation of velocity, temperature and any other variables throughout the region was studied. Results can be providing the engineer an understanding of the behavior of the fluid throughout the region of interest. This can lead to design modifications which can be tested by changing the geometry of the CFD model and seeing the effect.

The process of performing a single CFD simulation can be divided into.

1. Creating the Geometry/Mesh, as shown in Fig. (1, 2).
Table (1) shown how to select mesh properties.
2. Defining the Physics of the Model and boundary conditions created (inlet, outlet, absorber wall and fluxed wall).
3. Solving the CFD Problem.
4. Visualizing the Results in the Post-processor, as shown in Fig. (3).

Five different cross-sectional shapes as shown in Fig. (4,5) were studied under the same boundary conditions and same physics model used and one variable varied to study the effect of this variation with the thermal performance.

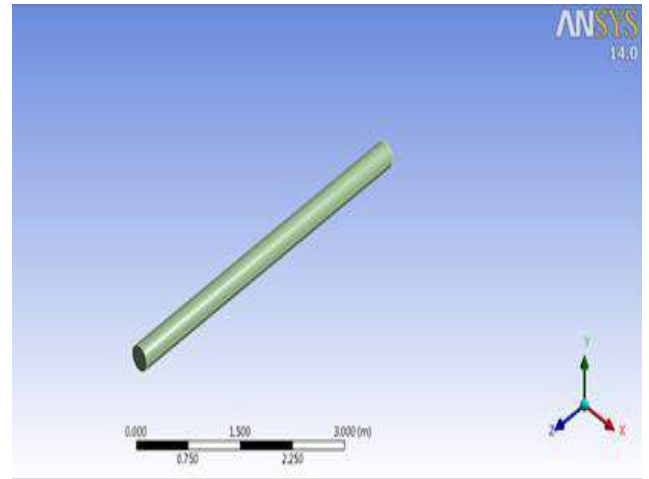


Fig. 1. The geometry of circular air heater.

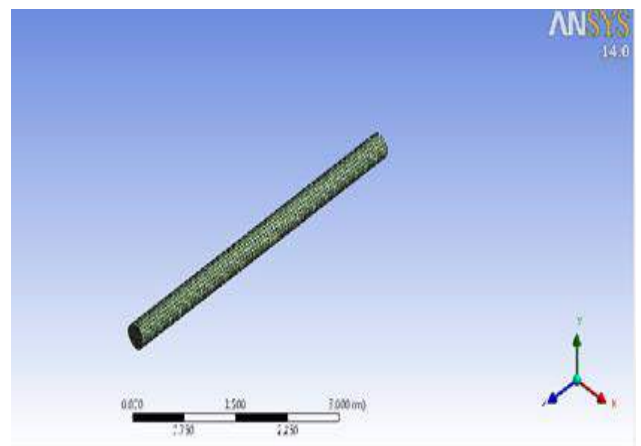


Fig. 2. Mesh of circular air heater.

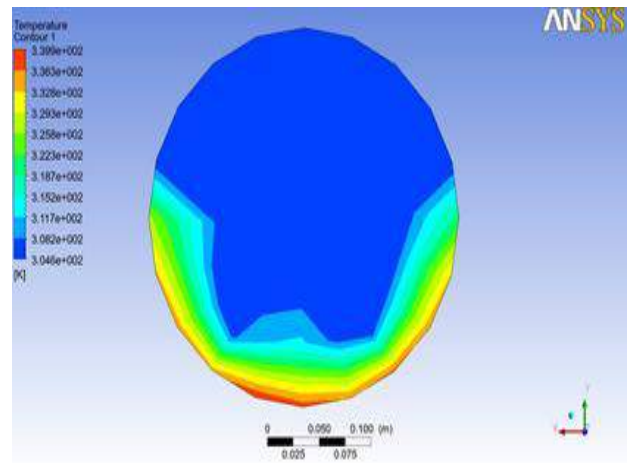


Fig. 3. Out let profile obtained in one of the simulation.

Table 1. selection of mesh sizing for tested simulating.

Max face size	No. of grids		Outlet temperature	Error %
	Nods	Element		
0.035	60321	55221	345.18	-
0.045	40495	35076	346.42	0.35
0.055	37620	33352	346.796	0.1
0.065	21948	18356	346.852	0.01
0.075	18630	14792	346.858	0.0017

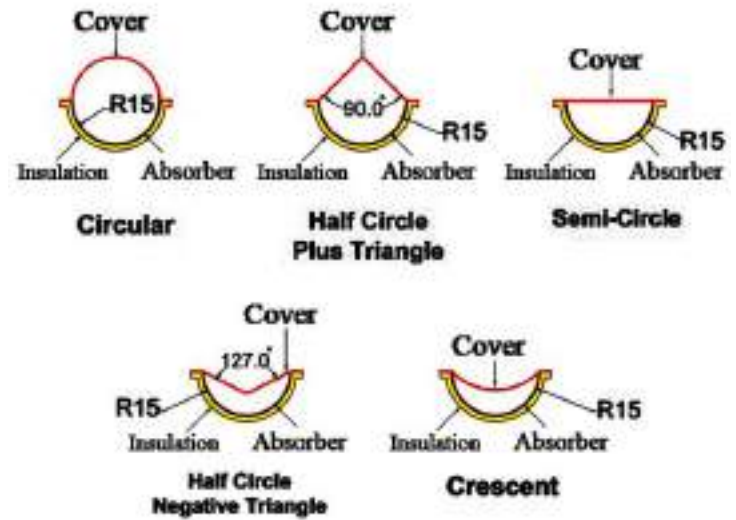


Fig. 5. The different five cross section area of tested solar air heaters.

Table 2: Definition for studied five shapes

parameter	Circular	Half circle + triangle	Semi-circle	Half circle - triangle	Crescent
Cross section area (A_c), m^2	0.071	0.058	0.035	0.024	0.023
Premeter (p), m	0.942	0.896	0.771	0.807	0.805
$D_{hydraulic}$, m	0.3	0.258	0.18	0.118	0.1143
Diameter, m	0.3	0.3	0.3	0.3	0.3
Cover surface area, m^2	9.42	8.48	6.0	6.72	6.66
Absorber surface area (A_p), m^2	9.42	9.42	9.42	9.42	9.42

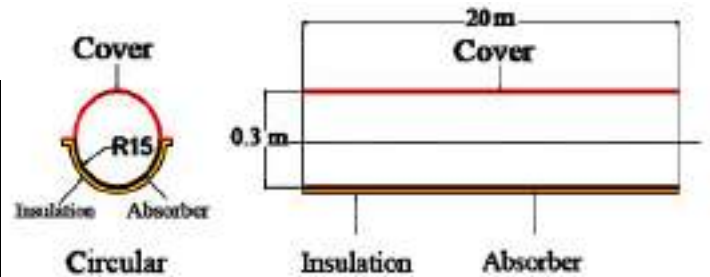


Fig. 4. Circular model (L=20m, D=0.3m)

2.1 Effect of inlet air velocity:

Studying the effect of variation of air inlet velocity through SAHs from 0.25 to 2.0 ($m.s^{-1}$) with a constant solar radiation intensity flux $I=850 (W.m^{-2})$ on the thermal performance of solar air heaters. The boundary condition for this tested case is shown in table (3). In this study the outlet temperatures (T_{out}) represent the main parameter.

Table 3: The boundary condition for studding the effect of air inlet velocity.

Domain	Boundary conditions	Value
Inlet	Temperature	32.9 °C
	Air flow velocity	0.25, 0.5, 1.0, 1.5, 2.0 m.s ⁻¹
Outlet	Ref. Pressure	1.0 atm
Absorber	Heat transfer	0.0 W.m ⁻²
cover	Heat transfer	850 W.m ⁻²

2.2 Effect of solar radiation:

Studding the effect of variation of solar radiation intensity from 400 to 1200 (W.m⁻²) with a constant inlet air velocity $V = 1.0$ (m.s⁻¹), on the thermal performance of solar air heaters. The boundary condition for this tested case is shown in table (4). In this study the outlet temperatures (T_{out}) represent the main parameter.

Table 4: The boundary condition for studding the effect of solar radiation intensity.

Domain	Boundary conditions	Value
Inlet	Temperature	32.9 °C
	Air flow velocity	1.0 m.s ⁻¹
Outlet	Ref. Pressure	1.0 atm
Absorber	Heat transfer	0.0 W.m ⁻²
cover	Heat transfer	400, 600, 800, 1000, 1200 W.m ⁻²

2.3 Comparison between present numerical results and previews experimental data at same conditions:

Abdullah et al. [19] used different cross sectional for solar air heater (circle, semi-circle, half circle-plus isosceles triangle) as shown in figure (6,7). The thermal performance studied with varied mass flow rate experimentally they concluded that the highest efficiencies were accomplished for circular shape and reached to about 80.2% at mass flow rate 0.25 (kg.s⁻¹) and at the same working conditions the efficiencies for the other shapes were respectively (70.6% and 50.6% for half circle-plus isosceles triangle and semi-circle), in this case we studied the same three shape (circle, semi-circle and half circle-plus isosceles triangle) with absorber length 5.0 m , diameter 0.3 m and emissivity coefficient 0.98 at same worked condition of their experimental search they varied the mass flow rate through the SAHs from 0.05 to 0.25 (kg.s⁻¹) with a constant solar radiation intensity 950 (W.m⁻²) to make a comparison between a numerical studied and their experimental studied. The boundary condition for this tested case is shown in table (5).

Table 5: The boundary condition for studying the effect of mass flow rate through in SAHs.

Domain	Boundary conditions	Value
Inlet	Temperature	32.9 C°
	Air mass flow rate	0.05, 0.1, 0.15, 0.2, 0.25 kg. s ⁻¹
Outlet	Ref. Pressure	1.0 atm
Absorber	Heat transfer	0.0 W.m ⁻²
cover	Heat transfer	950 W.m ⁻²



Fig .7. The different three cross section area of tested solar air heater for verification. [19]

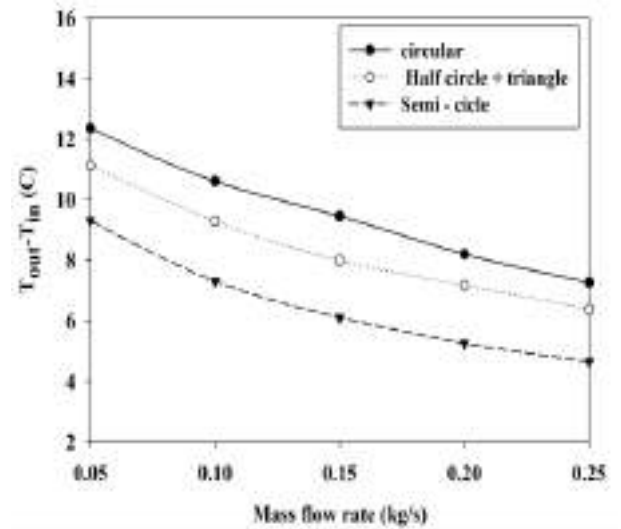


Fig.8.The variations of temperature difference with mass flow rate at constant solar radiation intensity 950 (W/m²) for different tested shape.

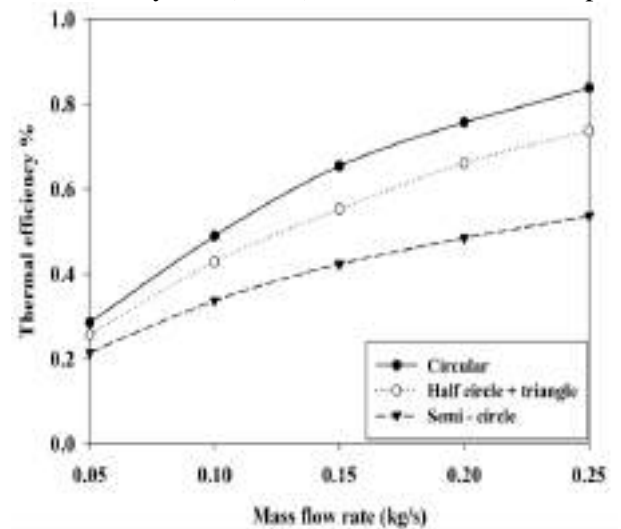


Fig.9.The variations of thermal efficiency with mass flow rate at constant at constant solar radiation intensity 950 (W/m²) for different tested shapes.

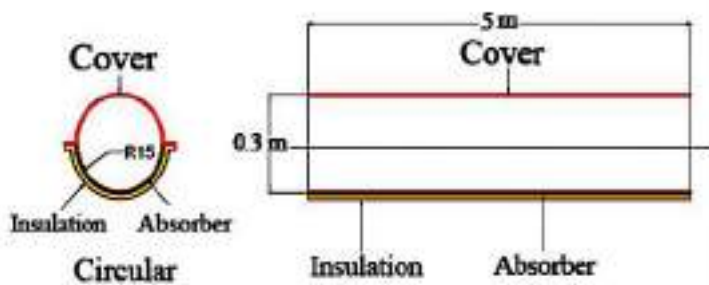


Fig .7. Circular model (L=5m, D=0.3m). [19]

The variation of mass flow rate at constant solar radiation intensity was done at various plastic solar heaters cross sectional Shapes to acquire the best efficiency. A comparison between the variations of temperature difference, between inlet and outlet air temperature ($T_{out} - T_{in}$) with mass flow rate (\dot{m}) at constant solar radiation intensity 950 (W.m⁻²) for circular, half-circle plus isosceles triangle, semi-circular is shown in Figure

(8).The figure indicated that the temperature difference decreases as mass flow rate (\dot{m}) increase at a constant solar radiation intensity 950 (W.m^{-2}). It was found that the temperature difference for the circular shape is higher than half circle-plus isosceles triangle, by the same way the half circle-plus isosceles triangle is higher than semi-circle. Also from Figure (8). It could be noted that at mass flow rate 0.05 (kg.s^{-1}) and solar radiation 950 (W.m^{-2}) the temperature differences was about 12.36 °C for circular shape air heater.

A comparison between the thermal efficiency for the three cross section shapes (circular shape, half circle-plus isosceles triangle and semi-circular) had the same absorber cross section area. The tested solar air heaters as a function of mass flow rate (\dot{m}) through air heaters at constant solar radiation intensity 950 (W.m^{-2}) is shown in Figure (9). As shown it can be noticed that by increasing mass flow rate (\dot{m}) the thermal efficiency for the air solar heaters increases. Also, it can also be observed that the rate of increasing the thermal efficiency is very high at lower air flow rate range 0.05–0.15 (kg. s^{-1}). The energy loss by heat transfer to fluid increases with increasing the mass flow rate (i.e. increasing the Reynolds number).The figure indicated that the circular solar air heater had better efficiency compared with semi-circular plus triangle air heaters and semi-circular air

heaters. This due to the circular solar air heater had the highest energy transfer because of having the largest cross section area.

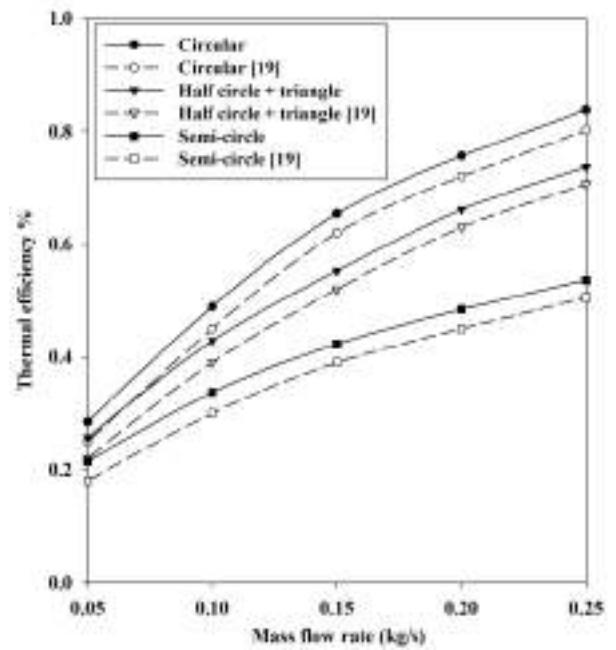


Fig.10.The variations of thermal efficiency with mass flow rate at constant at constant solar radiation intensity 950 (W.m^{-2}) for different tested shapes numerical and experimental results verification.

A comparison between present work and Abdullah, et al. [19] experimental study at same boundary conditions is shown in Figure (10) As shown it can be noticed that the circular shape had the best thermal efficiency numerically and experimentally and the results for the both searches were converged and the error between them as shown in figure (10) at range from 2.96% to 3.80%.

2.4. Governing Equations

Governing equations which are used by the ANSYS software are illustrated here.

2.4.1. Continuity equation

$$\partial\rho/\partial t + \nabla \cdot (\rho U) = 0 \quad (1)$$

2.4.2. Momentum equation

$$\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho U \times U) = -\nabla P + \nabla \cdot \tau + S_M \quad (2)$$

Where the stress tensor, τ , is related to the strain rate by

$$\tau = \mu \left(\nabla U + (\nabla U)^T - \frac{2}{3} \delta \nabla \cdot U \right) \quad (3)$$

2.4.3. Total energy equation

$$\frac{\partial(\rho h_{tot})}{\partial x} - \frac{\partial\rho}{\partial t} + \nabla \cdot (\rho U h_{tot}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (U \cdot \tau) + U \cdot S_M + S_E \quad (4)$$

Where h_{tot} is the total enthalpy, related to the static enthalpy $h(T, P)$ by.

$$h_{tot} = h + \frac{1}{2} U^2 \quad (5)$$

The term $\nabla \cdot (U \cdot \tau)$ represents the work due to viscous stresses and is called the viscous work term.

The term $U \cdot S_M$ represents the work due to external momentum sources and is currently neglected.

2.4.4. Reynolds no (Re). Calculation

$$Re = \rho V D / \mu \quad (6)$$

$$D = \frac{4A}{P}$$

2.4.5. Mass flow rate (\dot{m}) through the SAHs can calculate from

$$\dot{m} = \rho V A_c \quad (7)$$

2.4.6. The SAHs thermal efficiency obtained as follow:

$$\begin{aligned} \zeta &= \frac{\text{Useful energy delivered}}{\text{Total incoming solar energy}} \\ &= \frac{\dot{m} C_P (T_{out} - T_{in})}{A_P I_C} \end{aligned} \quad (8)$$

Where, A_p the absorber area

$$A_p = \pi r L$$

3. Results and Discussions

3.1 The variation of inlet air velocity at constant solar intensity radiation:

The variation of inlet air velocity at constant solar intensity radiation was done at various plastic solar heaters cross sectional Shapes to acquire the best thermal efficiency. A comparison between the variations of temperature difference between inlet and outlet air temperature ($T_{out} - T_{in}$) with velocity of air flow through solar air heater cross sectional shapes shown in Figure (11). The figure indicated that the temperature difference decreases as the velocity of flow air increases because of increasing the Reynolds number. Higher Reynolds number increases the turbulent flow that improves energy transfer to air. It is found that the temperature difference for the crescent shape was the highest, this is because of the crescent shape has the smallest mass flow rate due to the crescent shape had the smallest cross section area. Also, from Figure (11) it could be noted that solar intensity 850 ($W \cdot m^{-2}$) and air flow velocity

0.25 (m.s⁻¹) the temperature differences was about 86.16 °C for crescent shape air heater.

A comparison between the thermal efficiency for the five tested solar air heaters as a function of inlet air velocity at constant solar radiation intensity 850 (w.m⁻²) shown in Figure (12). It can be noticed from that by increasing velocity of air flow the thermal efficiency for the air solar heaters increases. The figure indicated that the circular solar air heater had the best thermal efficiency compared with others four cross sectional shapes. Because of the circular shape have the largest cross-sectional area so the circular solar air heater has higher energy transfer than the other four shapes.

3.2 The variation of solar radiation intensity at constant inlet air velocity:

The variation of solar radiation intensity at constant velocity was done at various plastic solar heaters cross sectional Shapes to acquire the best thermal efficiency. A comparison between the variations of temperature difference between inlet and outlet air temperature ($T_{out} - T_{in}$) with solar radiation intensity at a constant air velocity 1.0 (m.s⁻¹) as shown in Figure (13). The figure indicated that the temperature difference increases as solar radiation intensity increase at a constant

velocity 1.0 (m.s⁻¹).It is found that the temperature difference for the crescent shape was the highest compared with others shapes This is because at velocity of air flow 1.0(m.s⁻¹) the mass flow rate (\dot{m}) within crescent the shape 0.0393 (Kg.s⁻¹) is lower than that for half circle-negative isosceles triangle 0.041(Kg.s⁻¹), semi-circular shape 0.059 (Kg.s⁻¹), half circle-plus isosceles triangle 0.099 (Kg.s⁻¹) and circle shape 0.121 (Kg.s⁻¹). And every cross-sectional shape the mass flow rate (\dot{m}) through in was a constant whatever solar intensity varied from 400 to 1200 (w.m⁻²). Also, from this figure it could be noted that solar intensity 1200 (W.m⁻²) and air flow velocity 1.0 (m.s⁻¹) the maximum temperature differences was about 89.09 °C for crescent air heater.

A comparison between the thermal efficiency for the five tested solar air heaters as a function of solar radiation intensity at constant inlet air flow velocity 1.0 (m.s⁻¹) as shown in figure (14). As shown it can be noticed from that by increasing solar radiation intensity the thermal efficiency for the air solar heaters increases. The figure indicated that the circular solar air heater had the best efficiency compared with other four cross sectional shapes Because of the circular shape had the largest cross-sectional area so it had higher energy transfer than the other four shapes.

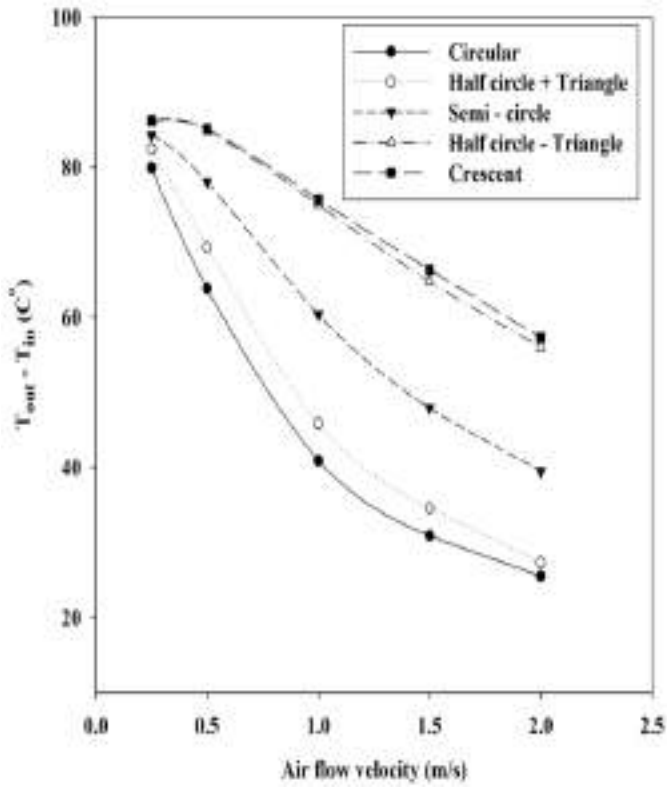


Fig.11.The variations of temperature difference with air inlet velocity at constant solar radiation intensity 850 (W/m²) for different tested shapes.

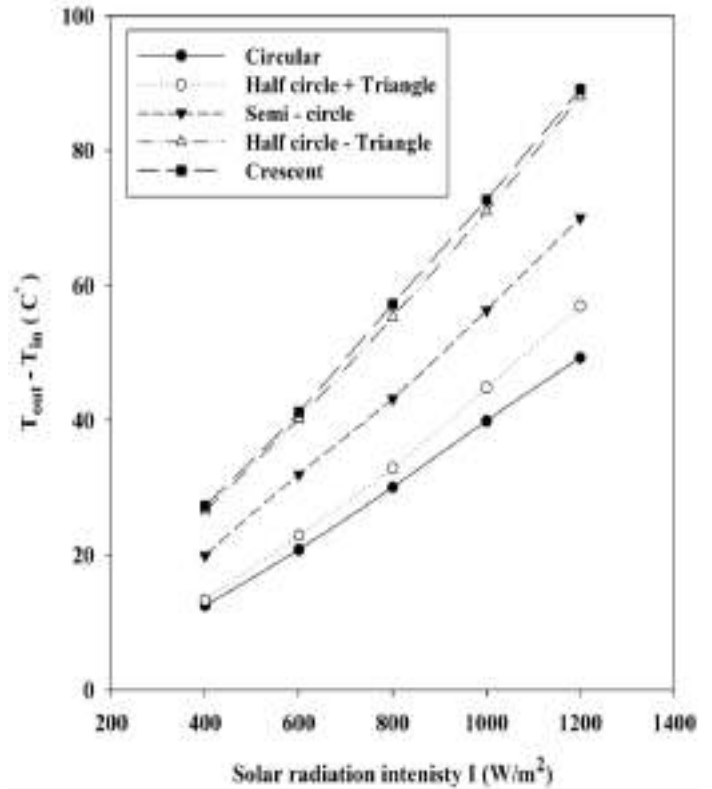


Fig.13.The variations of temperature difference with solar radiation intensity at constant inlet air velocity 1.0 (m/s) for different tested shapes.

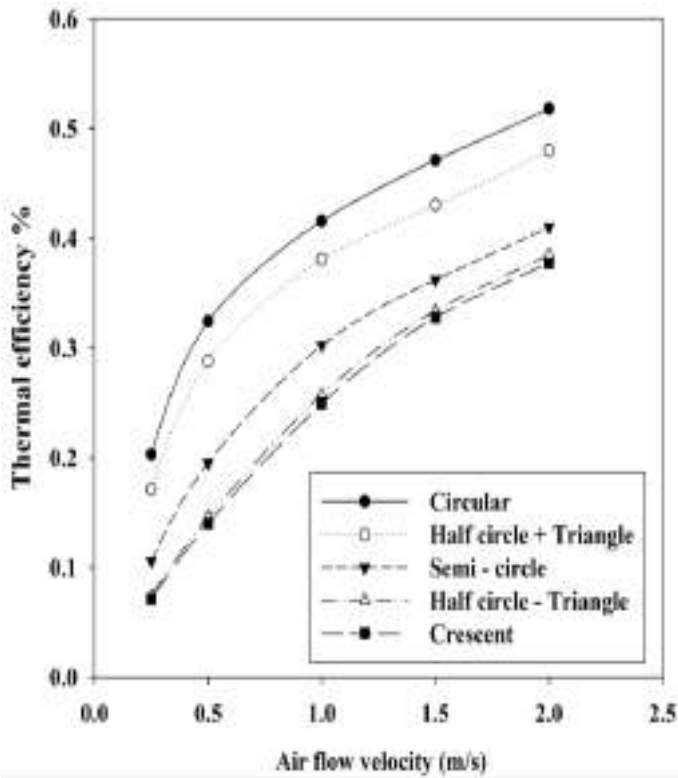


Fig.12.The variations of thermal efficiency with air inlet velocity at constant solar radiation intensity 850 (W/m²) tested SAHs shapes.

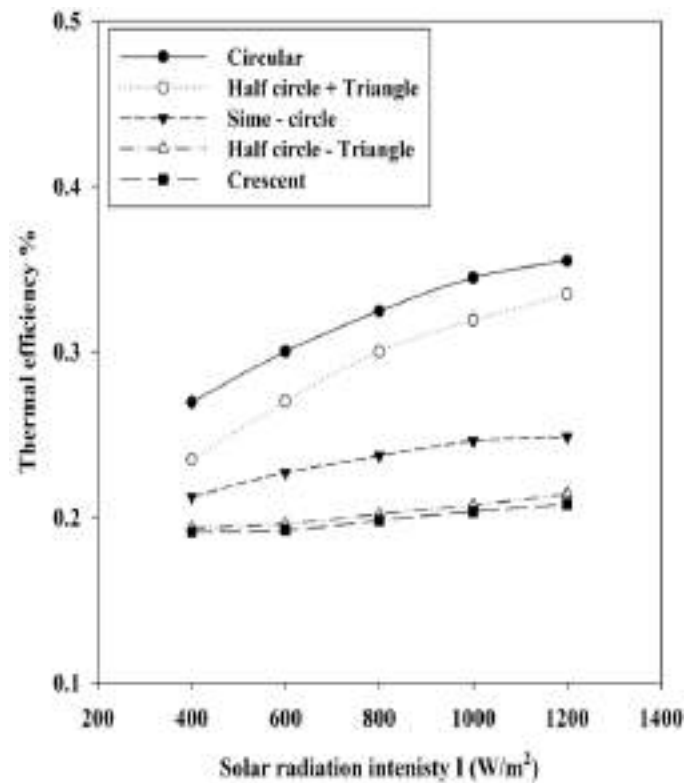


Fig.14.The variations of thermal efficiency with solar radiation intensity at constant air inlet velocity 1.0 (m/s) tested SAHs shapes.

4. Conclusions

The numerical study of plastic SAHs with different configurations was tested by ANSYS 14.0, the effect of variation the inlet air flow velocity at constant solar radiation intensity and the effect of variation solar radiation intensity at constant air flow velocity on the thermal performance of the plastic SAHs were examined.

- The results indicated that the highest efficiencies were achieved for the circular configuration and reach about 51.79% at air flow velocity of 2.0 (m.s⁻¹) and a constant solar radiation of 850 (W.m⁻²). The thermal efficiency reached about 41.3% for half-circle plus isosceles triangle shape, 38.48% for semi-circular shapes, 38.4% for half circle-negative isosceles triangle shape and 37.72% for crescent shape.
- At solar radiation 1200(w.m⁻²) and a constant air flow velocity 1.0 (m.s⁻¹) the circular air heater had thermal efficiency about 35.51%, half circle-plus isosceles triangle air heater about 33.47%, semi-circular air heater about 24.85%, half circle-negative isosceles triangle air heater about 21.41% and crescent air heaters about 20.78%.
- The verification between present work and Abdullah et al. [19] indicated that results

were converged and the error between them at range from 2.96% to 3.80%.

Nomenclature

- A_c : Cross section area of solar air heaters.
 A_p : Absorber surface area (m²).
 C_p : Specific heat of air (J.kg⁻¹.K⁻¹).
 D : The hydraulic diameter of the cross sectional shapes (m).
 I_c : The solar radiation intensity (W.m⁻²).
 L : The solar air heater absorber length.(m)
 \dot{m} : The mass flow rate (kg. s⁻¹).
 P : Perimeter of sectional shapes (m).
 T_{out} : The outlet temperature (K°).
 T_{in} : The inlet temperature (K°).
 V : The velocity of air flow (m.s⁻¹).
 ρ : The density of air flow (kg. m⁻³).
 μ : The viscosity of air flow (N.s.m⁻²).
 ζ : The thermal efficiency.

Abbreviations

SAH: Solar air heater.

SAHs: Solar air heaters.

A CFD: computational fluid dynamics.

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