PERFORMANCE AND COST ANALYSIS OF DOUBLE DUCT SOLAR AIR HEATERS

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Abstract— This study involves a model to investigate the effect of mass flow, channel depth and collector length on the thermal performance and cost benefit ratio for two types of solar air heaters in double flow mode, flat plate collector with porous media and V-groove absorber. The thermal performance was determined over a wide range of operating conditions. It is found that the double pass double duct V-groove absorber is 4% -15% more efficient than the double pass flat plate collector with porous media in the lower duct and the outlet temperature is increased by 2^{o}C -8^{o}C even though it had a porous media in flat plate collector. On the other hand it is concluded that the higher in cost energy for any particular combination of flow depth, collector length and mass flow rate is at short collector length, small flow depth with high quantity of mass flow rate. Moreover, the values of duct lengths and depths for which the cost of solar energy is minimized are different for different values of mass flow rates

Key words— Flat plate collector, V-groove absorber, Thermal performance, Cost of solar energy.

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1. INTRODUCTION

Extensive investigations have been carried out on the optimum design of conventional and modified solar air heaters, in order to search for efficient and inexpensive designs suitable for mass production for different practical applications. The researchers have give their attention to the effects of design and operational parameters, type of flow passes, number of glazing and type of absorber flat, corrugated or finned on the thermal performance of solar air heaters [1-4]. Additional studies to determine the thermal performance of solar air heaters have been conducted theoretically and/or experimentally, and different modifications are suggested and applied to improve the heat transfer coefficient between the absorber plate and air [5-9]. However, the availability of a tool to be used for supporting the designs of solar air heaters, application of mathematical models for the analysis of descriptive data from the domain experts would facilitate the task. A developed Mathematical model to predict the thermal performance and cost effectiveness for different designs of solar air heaters was presented [10] and [11]. This study uses the aforementioned developed model to find the influence of different parameters, such as mass flow rate, flow channel depth and collector length on the system thermal performance and the cost benefit for two types of solar air heaters in double flow mode, these types are flat plate collector with porous media and V-groove absorber

2. THEORETICAL ANALYSIS

In this section, the heat transfer and the cost factors of the double pass solar air heaters are discussed, which lead to annual thermal energy gain (ATEG) and annual cost (AC) of the systems. The cross sectional views and the thermal network of the two solar air heaters are illustrated in Figure 1. In the two types, the air heaters are composed of three plates, the cover, the absorber and the rear or back plate. The lower duct has been packed with a porous media of 0.80 porosity in type 1. The various heat transfer coefficients at different components of the air heaters are illustrated in the thermal network in Figure 1. To model the solar air types and obtain there relative equations, analysis is based on energy balance at various components of the collector models, along with the different heat transfer coefficients at their surfaces. The assumptions made are:

i. Heat transfer is steady and one dimensional
ii. The temperatures of the glass, absorber and bottom plates vary only along the x-direction of the air flow
iii. There is no leakage from the smooth flow channels
iv. The absorption of solar radiation in the cover is neglected insofar as it affects loss from the collector
v. Heat losses through the front and back of collector are to the same ambient temperature

At some location a long the flow direction, the absorbed solar energy heats up the plate to a temperature T_p.
In the flat plate collector with porous media, energy is transferred from the plate at T_P to the cover through the radiation heat transfer coefficient h_{r1}, to the fluid in the upper duct through the convection heat transfer coefficient h_2, and to the fluid in the lower duct through the convection heat transfer coefficient h_3. Energy is also transferred to the porous media through the radiation heat transfer coefficient h_{r2}. Energy is transferred from the porous media to the fluid in the lower duct through the convective heat transfer coefficient h_4. Energy is transferred from the fluid flowing in the upper duct at T_{f1} to the cover through the convection heat transfer coefficient h_1, and from the fluid in the lower duct at T_{f2} to the base plate through convection heat transfer coefficient h_5. Energy also is transferred from the porous media to the bottom plate through the convection heat transfer coefficient heat transfer coefficient h_6. Finally energy is lost to the ambient air through the combined convection and radiation coefficient U_t through the cover glass. Figure 1(a) illustrates the double pass double duct flat plate collector with porous media in the lower duct and the thermal network. The steady-state energy balance gives the following equations:

Collector cover

$$h_1(T_{f1}-T_c)+h_{r1}(T_p-T_c)=U_t(T_c-T_a) \quad (1)$$

Fluid 1

$$h_2(T_p-T_{f1})=(\frac{\dot{m}C_{p1}}{W})(\frac{dT_{f1}}{dx})+h_1(T_{f1}-T_c) \quad (2)$$

Absorber

$$I\tau\alpha = h_{r1}(T_p - T_c) + h_2(T_p - T_{f1}) + h_3(T_p - T_{f2}) + h_{r2}(T_p - T_{pr}) \quad (3)$$

Fluid 2

$$h_3(T_p - T_{f2}) = (\frac{\dot{m}C_{p2}}{W})(\frac{dT_{f2}}{dx}) + h_4(T_{pr} - T_{f2}) + h_5(T_{f2} - T_r) \quad (4)$$

Porous media

$$h_{r2}(T_p - T_{pr}) + h_6(T_{pr} - T_r) = h_4(T_{pr} - T_{f2}) \quad (5)$$

Bottom plate

$$h_5(T_{f2} - T_r) + h_6(T_{pr} - T_r) = U_b(T_r - T_a) \quad (6)$$

For V-groove absorber energy is transferred from the plate at T_P to the cover through the radiation heat transfer coefficient h_{r1} and the convection heat transfer h_1, and to the fluid in the upper duct flowing through the V-groove at a temperature T_{f1} through the convection heat transfer coefficient h_2, and to the fluid in the lower duct flowing between the absorber plate and the base plate at a temperature T_{f2} through the convection heat transfer coefficient h_3. Energy also is transferred to the base plate through the radiation heat transfer coefficient h_{r2}. Energy is transferred from the fluid flowing in the lower duct at T_{f2} to the base plate through convection heat transfer coefficient h_4. Finally energy is lost to the ambient air through the combined convection and radiation coefficient U_t through the cover glass. Figure 1 (b) illustrates the double pass double duct V-groove absorber and the thermal net work. The steady-state energy balance on the cover, the plate and the fluid in the upper and lower gives the following equations:

Collector cover

$$h_1(T_p - T_c) + h_r(T_p - T_c) = U_t(T_c - T_a) \quad (7)$$

V-groove absorber

$$h_2(T_p - T_{f1}) + h_1(T_p - T_c) + h_r(T_p - T_c) + h_3(T_p - T_{f2}) + h_{r2}(T_p - T_r) = I\tau\alpha \quad (8)$$

Fluid medium in the upper passage

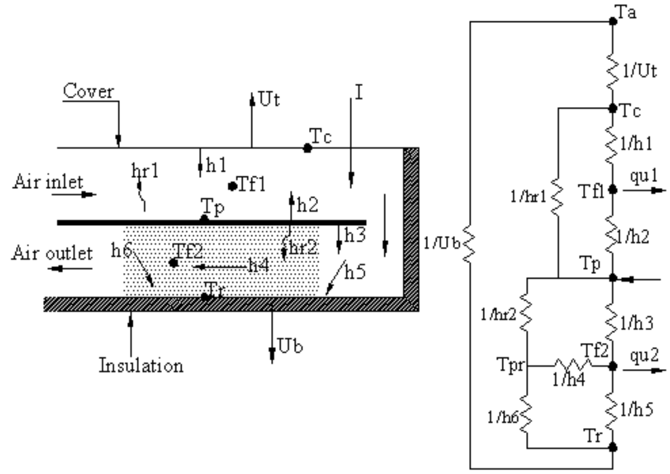
$$h_2(T_p - T_{f1}) = (\frac{\dot{m}C_{p1}}{W})(\frac{dT_{f1}}{dx}) \quad (9)$$

Fluid medium in the lower duct

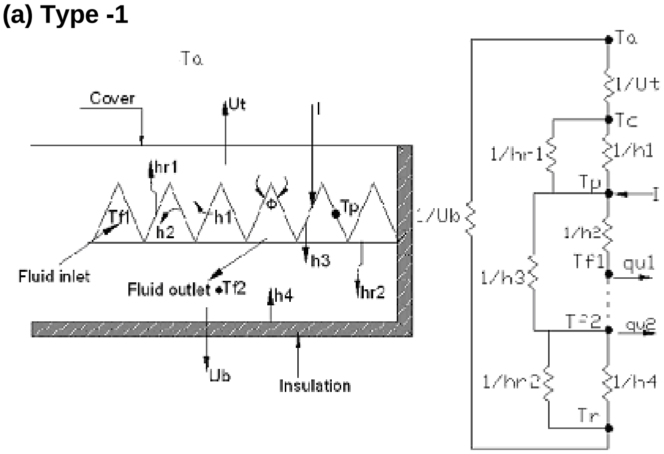
$$h_3(T_p - T_{f2}) = (\frac{\dot{m}C_{p2}}{W})(\frac{dT_{f2}}{dx}) + h_4(T_{f2} - T_r) \quad (10)$$

Bottom plate

$$h_4(T_{f2} - T_r) + h_{r2}(T_p - T_r) = U_b(T_r - T_a) \quad (11)$$



(a) Type -1



(b) Type -2

Figure 1: Schematic diagram of the solar air heaters with thermal network

2.1 Annual Energy Gain

The annual thermal energy gain (ATEG) available from the collector can be obtained by multiplying the useful heat by the number of operating days in a year and the number of hours per day during which useful sunshine is available [3].

$$ATEG = \dot{m}C_p(T_o - T_i)t_{op} \quad (12)$$

2.2 Annual Cost

In order to estimate the annual cost of the collector (AC) of the solar air different cost factors have to be calculated. This includes the annual pump cost or running cost (ARC), annual capital cost (ACC), annual maintenance cost (MC) and annual salvage value (ASV). The annual running cost is calculated as follows [1] and [2]:

$$ARC = (m_v \Delta p)t_{op}CE \quad (13)$$

Where ΔP is the pressure drop (Pa), t_{op} is the time of operation and CE is the cost of electricity (RM/KWh)

$$\Delta p = f\left(\frac{\dot{m}^2}{\rho}\right)\left(\frac{L}{D}\right)^3 \quad (14)$$

$$f = f_o + y\left(\frac{D}{L}\right) \quad (15)$$

The values of f_o and y are

$f_o = 24/\mathrm{Re}$, $y = 0.9$ for laminar flow (Re<2550)

$f_o = 0.0094$, $y = 2.92\,\mathrm{Re}^{-0.15}$ for transitional flow ($2550<\mathrm{Re}<10^4$)

$f_o = 0.059\,\mathrm{Re}^{-0.2}$, $y = 0.73$ for turbulent flow ($10^4<\mathrm{Re}<10^5$)

The annual capital cost (ACC) is given by the following relations:

$$ACC = CRFxCI \quad (16)$$

$$CI = CC + CSSC + FC \quad (17)$$

$$CRF = i(i+1)^n / [(i+1)^n - 1] \quad (18)$$

$$CC = WL*(X1+Y1) + (2D+W)*LZ1 \quad (19)$$

The annual salvage value (ASV) is given as:

$$ASV = SFFxSV \quad (20)$$

$$SFF = i/[(i+1)^n - 1] \quad (21)$$

$$SV = 0.1CI \quad (22)$$

Where CI is the Capital investment, SFF is the salvage fund factor and SV is the salvage value

Therefore, the annual cost of the collector (AC) is calculated as

$$AC = ACC + MC + ARC - ASV \quad (23)$$

3. Results and Discussion

To compare the performance of the solar air heaters a similar input data have been entered to give the same configuration for both double pass double duct flat plate collector with porous media in the lower duct and double pass double duct V-groove absorber. The detailed input data are given in Table 1

Table 1: Specification of Solar Air Heaters

Collector tilt angle (degree)	10
Collector length (m)	2.4
Collector width (m)	1.2
Plate type	Flat plate and V-groove of 45 degrees
Absorber material	Black steel, α = 0.9 and ε = 0.85
Cover material	Ordinary clear glass, τ = 0.85
Number of cover	1
Insulation material	Fiber glass , k = 0.045 W/m.k
Back insulation thickness (m)	0.05
Edge insulation thickness (m)	0.05
Porous media	Glass wall of 0.8 porosity for double pass with porous media in lower duct

Figure 2 and 3 shows the variation of efficiency and outlet temperature with mass flow rate for the two types of solar air heaters, the efficiency increased with the increase of mass flow rate as well as the outlet temperature decreased. The figures shows that the double pass double duct V-groove absorber is 4% -15% more efficient than the double pass flat plate collector with porous media in the lower duct and the outlet temperature is increased by 2°C -8°C even though it had a porous media in flat plate collector. This indicates that, the V-groove absorber has the significant advantage of absorbing a greater quantity of solar radiation than the flat plate of equal absorptivity and that because of the multiple reflections and absorption of incident radiation. Figure 4 shows the variation of pressure drop with mass flow rate, where the pressure drop in double pass V-groove absorber was less than that in double pass flat plate collector with porous media by 1 Pa to 4 Pa, hence, the use of porous media increase the pressure drop.

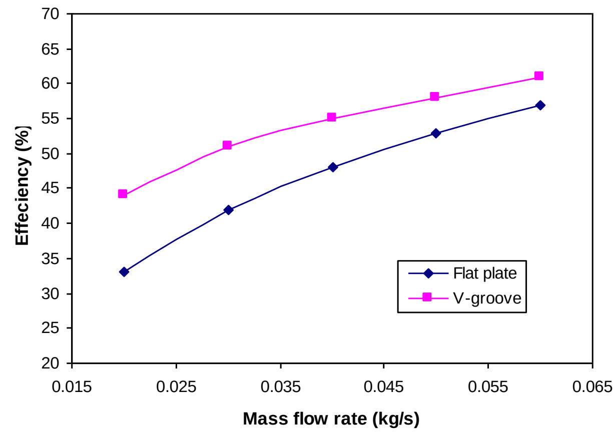


Figure 2: The Variation of Efficiency with Mass Flow Rate

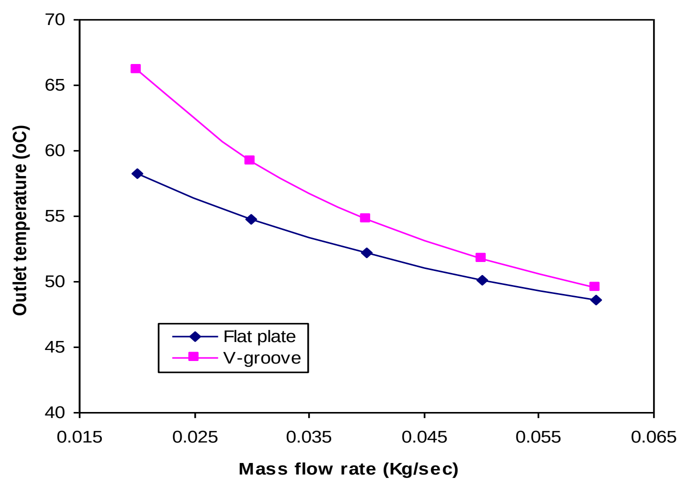


Figure 3: The Variation of Outlet Temperature with Mass Flow Rate

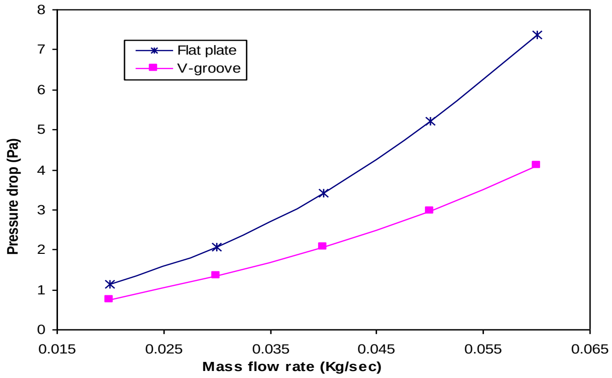


Figure 4: The Variation of Pressure Drop with Mass Flow Rate

The efficiency curves for double pass flat plate collector with porous media and double pass V-groove absorber at different flow rates are shown in Figures 5 and 6. The respective efficiency equations and F_R ($\tau\alpha$) and F_RU_L values are presented in Table 2 and 3. From the figures, it is evident that the slopes of the efficiency curves decrease with increase of flow rate, which means at higher flow rate, the overall loss is lower. Also it can be seen that the loss coefficient is higher in the double pass flat plate collector with porous media and least in V-groove collector for the same flow rate.

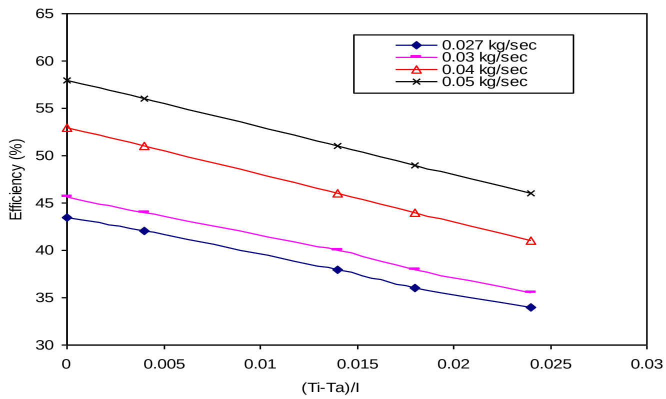


Figure 5: Efficiency Curve for Double Pass Flat Plate Collector with Porous Media in Lower Duct

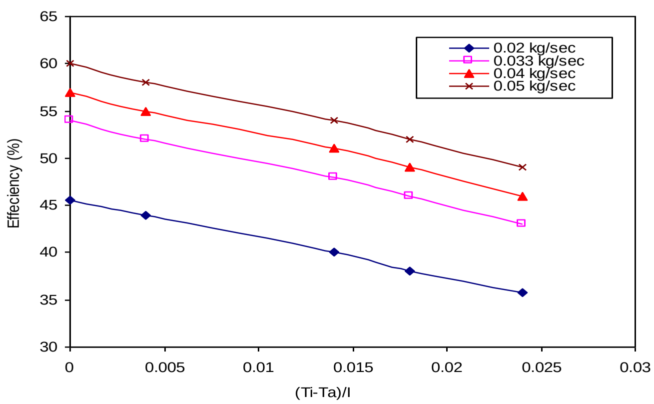


Figure 6: Efficiency Curve for Double Pass V-groove Absorber

Table 2: Efficiency Equations, F_R ($\tau\alpha$) and F_RU_L for Double Pass Flat Plate Collector with Porous Media in Lower duct

Flow rate (kg/s)	$F_R(\tau\alpha)$	F_RU_L	Efficiency equation	R^2
0.027	0.4342	4.1837	$y = -4.1837x + 0.4342$	0.9982
0.03	0.4582	4.1837	$y = -4.1837x + 0.4582$	0.9992
0.04	0.53	5	$y = -5x + 0.53$	1
0.05	0.58	5	$y = -5x + 0.58$	1

$x = (T_i - T_a)/I$ (Where T_i the inlet temperature, Ta the ambient temperature and I the solar isolation)

Table 3: Efficiency Equations, F_R ($\tau\alpha$) and F_RU_L for Double Pass V-groove Absorber without Porous Media in Lower Duct

Flow rate (kg/s)	$F_R(\tau\alpha)$	F_RU_L	Efficiency equation	R^2
0.02	0.4525	3.8776	$y = -3.8776x + 0.4525$	0.9989
0.033	0.5382	4.1837	$y = -4.1837x + 0.5382$	0.9977
0.04	0.5699	4.4898	$y = -4.4898x + 0.5699$	0.9977
0.05	0.5999	4.4898	$y = -4.4898x + 0.5999$	0.9977

$x = (T_i - T_a)/I$

By using the developed program, the cost of solar energy (i.e. ratio of the annual cost of the collector (AC) / annual thermal energy gain (ATEG) for the two solar air heaters types were computed at different flow depths and mass flow rate. Figure 7 illustrates the cost of solar energy with lower channel depth at fixed mass flow rate 0.04 kg/s, constant upper depth of 0.035 m and different flow lengths. The figure shows that the cost of solar energy is a function in collector length hence the cost is reduced by increasing the collector length.

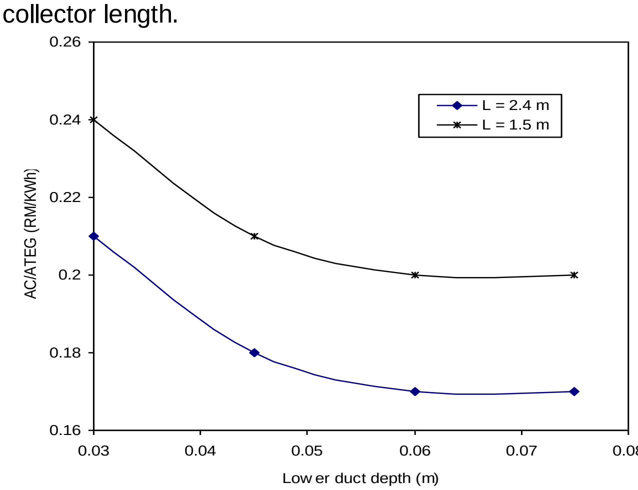


Figure 7: The Variation of AC/ATEG with Respect to Lower Flow Depth in Double Flow Flat Plate Collector with Porous Media.

Figure 8 shows the variation of the cost of solar energy as a function of lower channel depth for double flow mode with porous media for different mass flow rates. The Figure show that as the air mass flow rate increases, the cost of solar energy increases, which is becomes the highest at small flow depths at mass flow rate 0.05 kg/s. This is a consequence of the relatively larger rate of pumping cost than the rise of energy with a decrease in duct depth and an increase in air mass flow in the system.

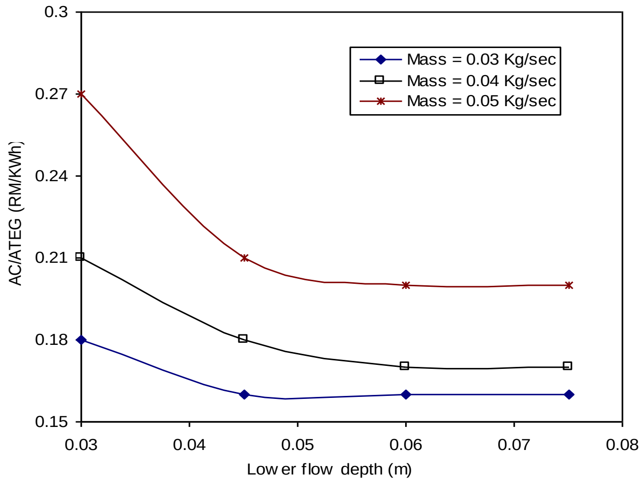


Figure 8: The variation of AC/ATEG with respect to lower flow depth in double flow flat plate collector with porous media.

The results obtained for V-groove absorber types are depicted in Figure 9. It shows the cost of solar energy as a function of lower flow depth with constant flow rate at 0.03 kg/s. The cost of solar energy with respect to flow depth at constant flow length and different mass flow rate are shown in Figure 10. The cost of solar energy decreased by increasing the flow depth, this decrease in the cost continue until it reach the minimum value then it begin to increase by increasing the flow depth. The graphs in all figures reveal that the higher in cost energy for any particular combination of flow depth, collector length and mass flow rate is at short collector length and flow depth with high quantity of mass flow rate. Moreover, the values of duct lengths and depths for which the cost of solar energy is minimized are different for different values of mass flow rates.

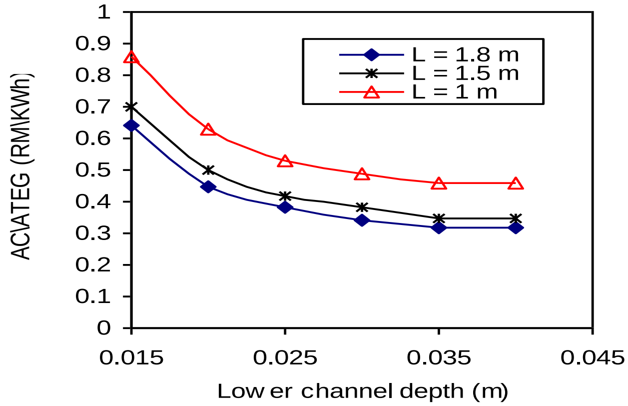


Figure 9: The variation of AC/ATEG with respect to lower flow depth for V-groove absorber.

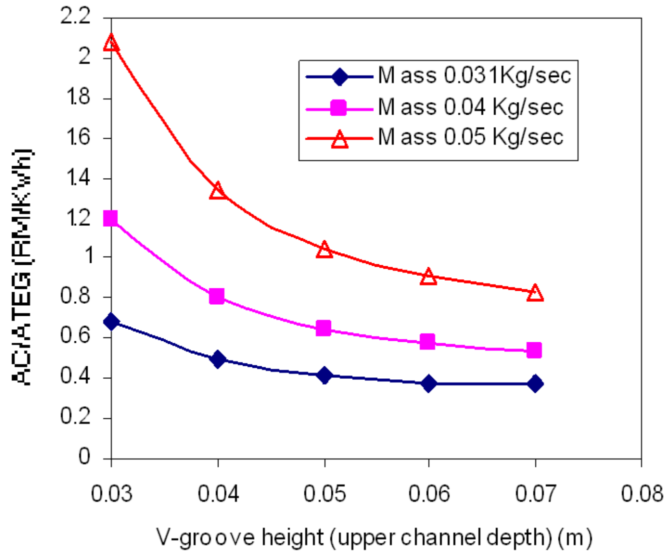
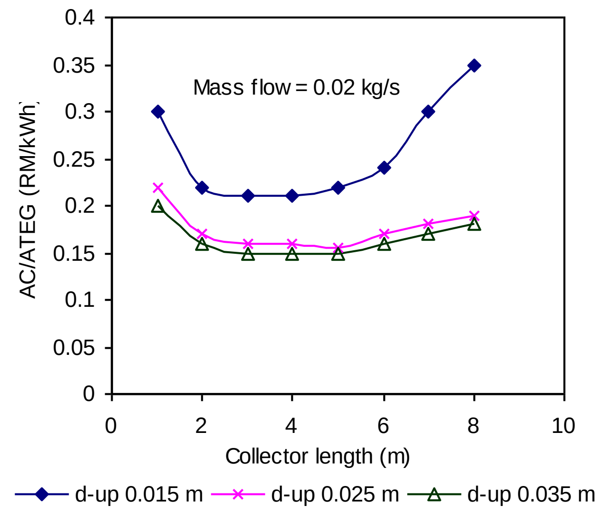
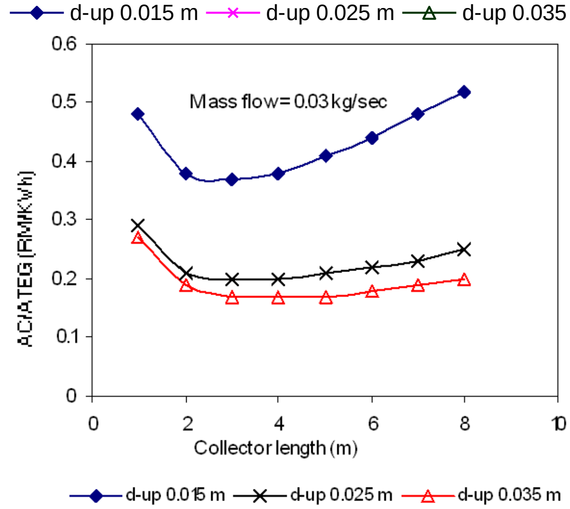


Figure 10: The variation of AC/ATEG with respect to flow depth for V-groove absorber for different mass flow rate.

The cost of solar energy as a function of collector lengths for fixed lower depth with different upper depth and for fixed upper depth with different lower depth for double flow flat plate collector with porous media in the lower duct are presented in Figures 11 and 12.





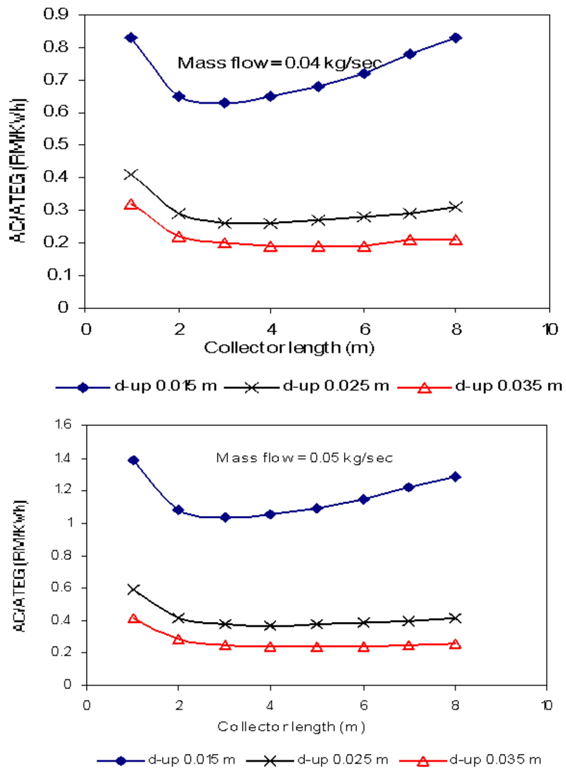


Figure 11: The AC/ATEG as a function of collector length for different upper depth and mass flow with constant lower depth in double flow pass flat plate collector with porous media.

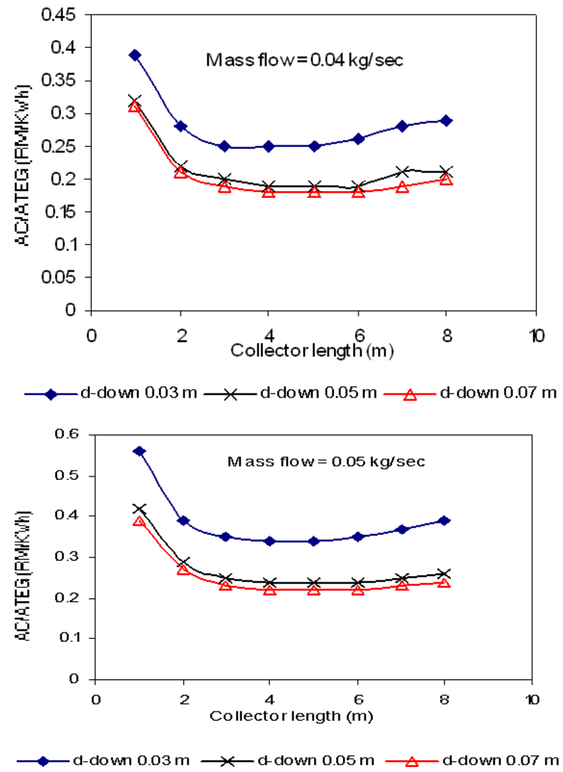
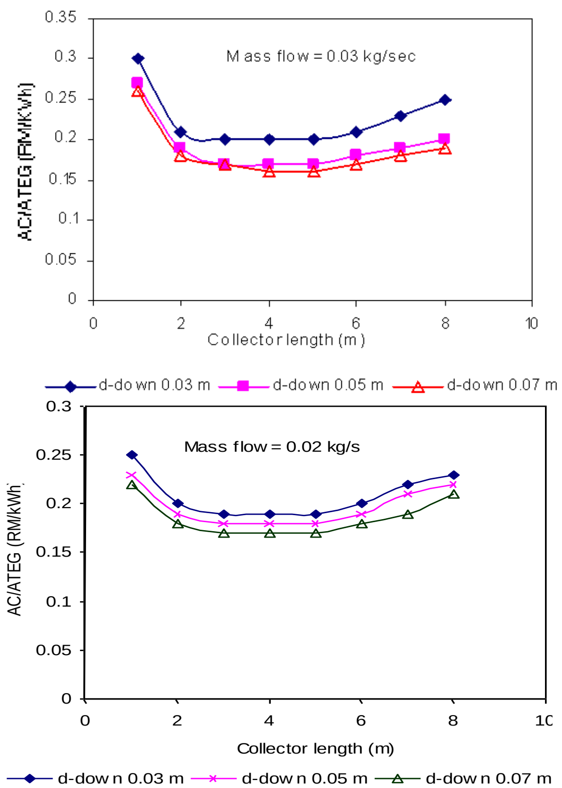


Figure 12: The AC/ATEG as a function of collector length for different lower depth and mass flow with constant upper depth in double flow pass flat plate collector with porous media.



The cost of solar energy as a function of collector lengths for fixed lower depth with different upper depth and for fixed upper depth with different lower depth for different air mass flow rates for the double pass V-groove absorber are presented in Figures 13 and 14.

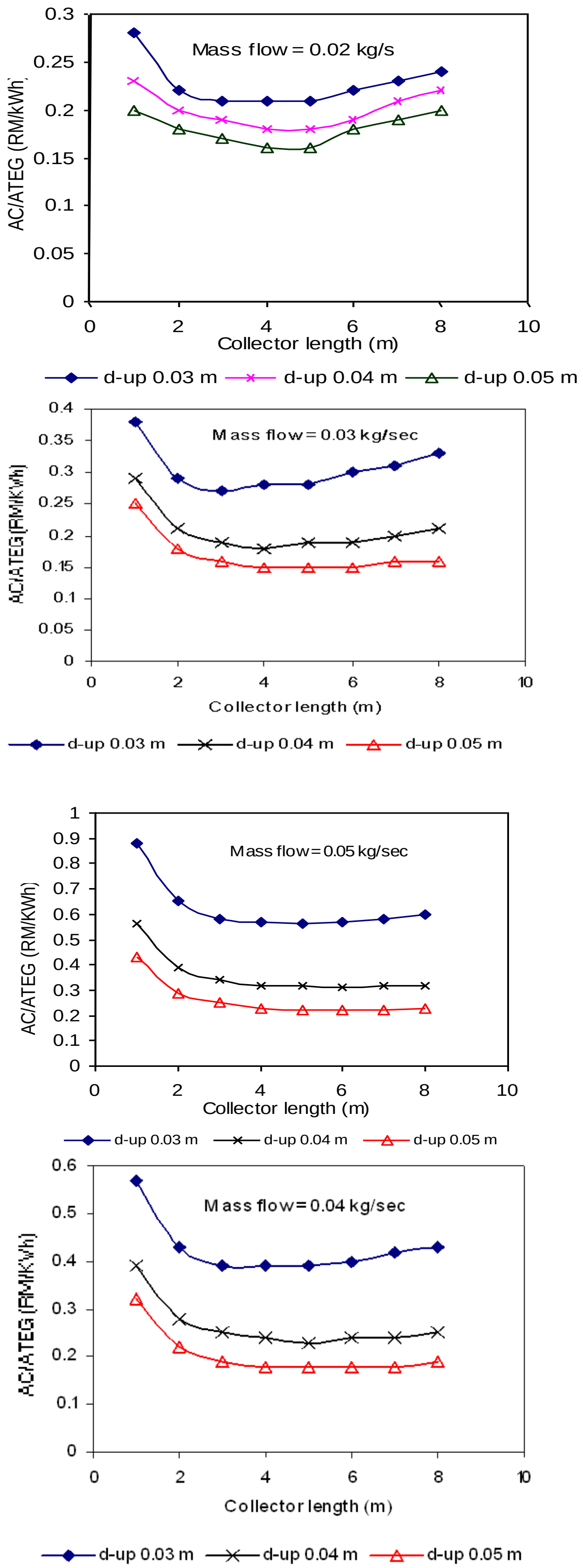


Figure 13: The AC/ATEG as a function of collector length for different upper depth and mass flow with constant lower depth in double flow pass V-groove absorber.

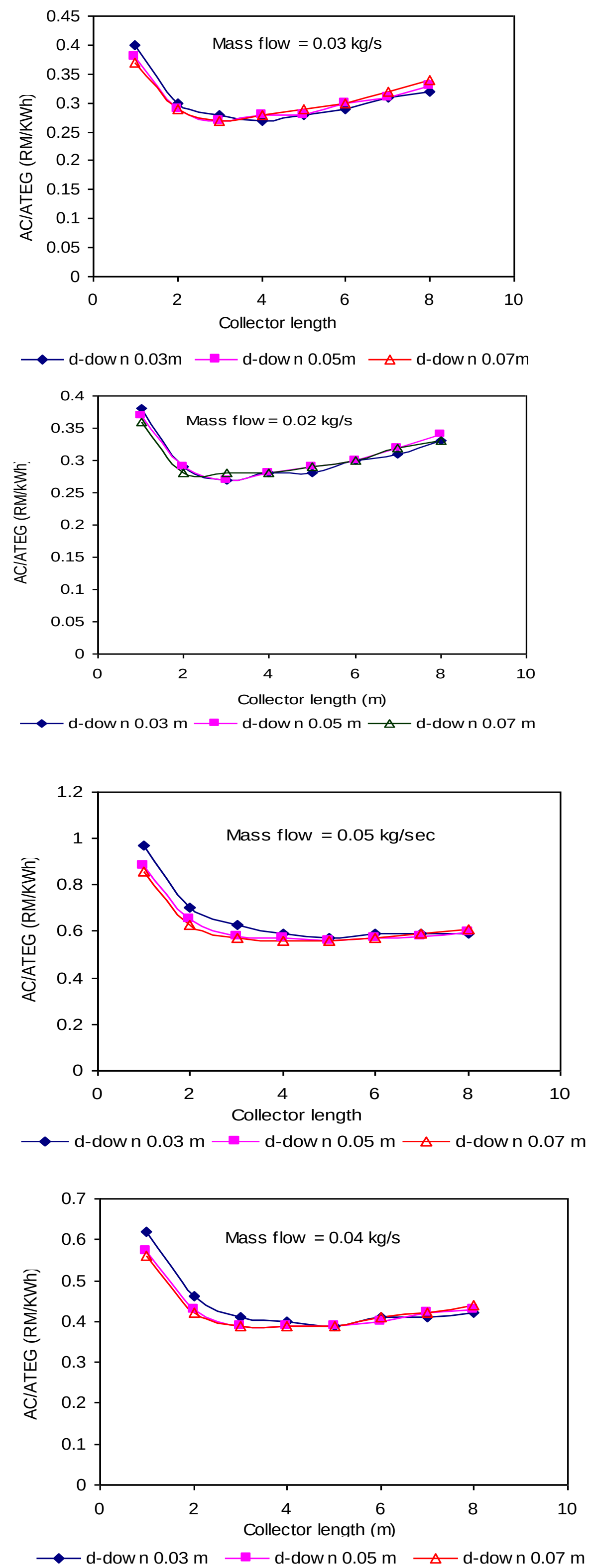


Figure 14: The AC/ATEG as a function of collector length for different lower depth and mass flow with constant upper depth in double flow pass V-groove absorber.

All the graphs 11-14 show at first a fall in the cost then a rise with an increase in length, the effect being greater with an increase in mass flow and a decreased in flow depth (Choudhury et al., 1995). The collector length for which the cost is minimized is observed to decrease with a decrease in collector depth and an increase in mass flow rate. Figure 15 is a direct comparison of the cost of the solar energy (AC/ATEG) for the double pass flat plate collector with porous media in the lower duct and the double pass V-groove absorber without porous media under identical design and operational conditions. It is shown that the cost of double pass flat plate collector with porous media is higher than that for double pass v-groove absorber in spite of higher energy gain is from the double pass V-groove absorber and that because of the large rate of rise of the pumping cost because of the use of porous media.

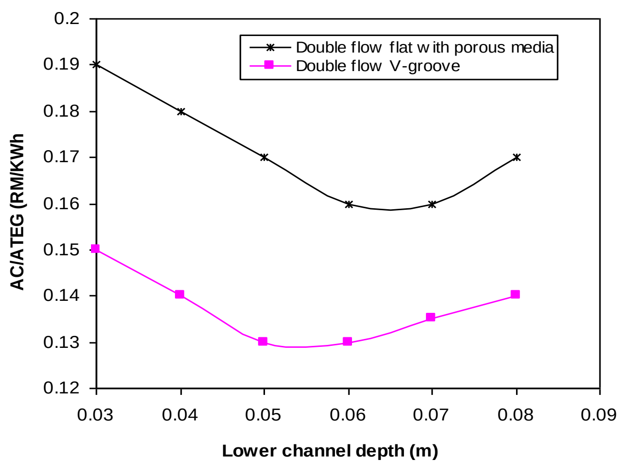


Figure 15: The AC/ATEG as a function of lower collector depth for double flow flat plat collector with porous media and double flow pass V-groove absorber without porous media.

The aforementioned discussed results on the effect of flow depth, length and mass flow rate on the cost of solar energy have the same trend of other studies conducted by [1-3] and [12].

4. Conclusion

From this study it is found that the parameters that affect thermal performance and the solar energy cost of the solar air heaters are mass flow rate, channel flow depth, collector length and the porous media. Their affective appears as follows:

1- Increasing the mass flow rate result in
   - i. Increasing the collector thermal efficiency
   - ii. Decreasing the outlet temperature
   - iii. Increasing the pressure drop, yet increase the cost of solar energy

2- Decreasing the flow depth cause
   - i. Increasing the collector thermal efficiency
   - ii. Increasing the outlet temperature
   - iii. Increasing the pressure drop which lead to an increase in the pumping expand in the collector thus increase the cost of solar energy

3- Increasing the collector length result in
   - i. Decreasing the collector thermal efficiency
   - ii. Increasing the outlet temperature
   - iii. Increasing the pressure drop

4- Using of porous media result in
   - i. Increasing the collector thermal efficiency
   - ii. Increasing the outlet temperature
   - iii. Increasing the pressure drop which lead to an increase in the pumping expand in the collector thus increase the cost of solar energy

Nomenclatures

ACC The annual capital cost, RM
CC The cost of the collector array, RM
CI The capital investment, RM
C_p Specific heat of working fluid, J/kg K
CRF The capital recovery factor
CSSC The collector support structure cost, RM
D Flow channel depth, m
FC The fabrication cost, RM
h Fluid heat transfer coefficient, W/m^2 K
h_r Radiation heat transfer coefficient, W/m^2 K
I Solar radiation, W/m^2
i The interest rate, assumed as 8%
L Collector length, m
$\dot{m}$ Collector flow rate, kg/s
m_v The volumetric rate, m^3/sec
MC The maintenance cost, considered to be 10% of the ACC.
n The collector life, assumed as 10 years
Q Rate of useful energy gain, W
T_a Ambient air temperature, K
T_c Cover temperature, K
T_f Fluid temperature, K
T_i Fluid inlet temperature, K
T_o Outlet temperature, K
T_p Absorber plate surface temperature, K
T_{pr} Porous media temperature, K
T_r Bottom plate temperature, K
U_b Back loss coefficient, W/m^2 K
U_t Top loss coefficient, W/m^2 K
W Collector width, m
X1 Cost of the absorber plate, RM/m^2
Y1 Cost of the cover, RM/m^2
Z1 Cost of side wall + bottom insulation, RM/m^2

Greek Symbols

τ Solar transmittance of glazing
α Solar absorptance of collector plate
ρ Density, kg/m^3

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