International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 6, August - 2012

PERFORMANCE ANALYSIS OF FLAT PLATE SOLAR AIR COLLECTORS WITH AND WITHOUT FINS

D. Bhandari[1] , Dr. S. Singh[2]
[1]M. Tech Scholar, [2]Associate Professor

Department of Mechanical Engineering,
Bipin Tripathi Kumaon Institute of Technology, Dwarahat, Almora, Uttarakhand (India) 263653

Abstract

The present work involves a comparative study of performance analysis of different types of flat plate solar air heaters. A **MATLAB** program code is generated to carry out the whole analysis. The effect of mass flow rates, inlet temperature and intensity of solar radiation on the performance of solar air heaters is also investigated in the present study. The three types of solar air heaters used for the analysis are: Conventional solar air heater, double glazing single pass solar air heater and double pass solar air heater with internal fins.

Keywords: *Conventional single pass solar air heater, Double pass solar air heater, Internal fins, Thermal efficiency, MATLAB.*

1. Introduction

Humans have always used the rays of the sun to gather their energy needs. In the energy needs of today with increasing environmental concern, alternatives to the use of non-renewable and polluting fossil fuels have to be investigated. One such possibility is solar energy, which has become increasingly popular in recent years. Various types of solar energy systems for agricultural and marine products have been reviewed [4]. One of the most important components of a solar energy system is the solar collector. Solar air collectors are simple, cheap and most widely used. Solar collectors can be used for drying, space heating, solar desalination, etc. 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 given 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 (Ratna et al. [10]; Ratna et al. [11]; Choudhury et al. [1]; Karim and Hawlader,

[8]). They concluded that for shorter duct lengths and lower air mass flow rates, the performance of the two pass air heaters with a single cover is most cost-effective as compared to the other designs. Helal *et al*. [6] studied energetic performances of an integrated collector storage solar water heater. The systems shows little cost, simplicity and simpler to be installed on the roof of the building. Fudholi et al.[3] conducted an experimental study on a forced- convective double-pass solar air collector with fins in the second channel. The experiments were conducted by changing the parameters that influence the thermal efficiency of the collector. Ho et al. [7] experimentally investigated a new device of inserting an absorbing plate to divide a flat-plate channel into two channels with fins attached and external recycling at the ends, resulting in substantially improving the heat transfer efficiency. The present work deals with comparing the performances of flat plate solar air heaters with and without fins using MATLAB computer software.

2. Mathematical Model

2.1 Conventional Solar air heater

The steady state energy balance conditions for the various parts of conventional flat plate solar air collector is given as

$$I_o\tau\alpha = U_t\left(T_{pm} - T_a\right) + h_1\left(T_{pm} - T_f\right) + h_r\left(T_{pm} - T_{bm}\right) \qquad (1)$$

$$h_r\left(T_{pm} - T_{bm}\right) = h_2\left(T_{bm} - T_f\right) \qquad (2)$$

$$\frac{m'C_p}{B}\frac{dT_f}{dx} = h_1\left(T_{pm} - T_f\right) + h_2\left(T_{bm} - T_f\right) \qquad (3)$$

Where, $h_r = \frac{4\sigma T_{av}^3}{\frac{1}{\square_p}+\frac{1}{\square_b}-1}$

Solving these equations we get

$$F' = 1 + \left(1 + \frac{U_t}{h_e}\right)^{-1} \qquad (4)$$

$$F_R = \frac{m'C_p}{U_tA_p}\left[1 - \exp\left\{-\frac{F'U_tA_p}{m'C_p}\right\}\right] \qquad (5)$$

$$Q_u = F_RA_p[I_0\tau\alpha - U_t(T_i - T_a)] \qquad (6)$$

$$\eta = \frac{Q_u}{I_0A_p} \qquad (7)$$

$$T_o = \left[Q_u/\left(C_pm'\right)\right] + T_i \qquad (8)$$

$$T'_{pm} = T_a + \left[\frac{I_0}{U_t}(\tau\alpha - \eta)\right] \qquad (9)$$

Mean fluid temperature is calculated by using the formula

$$T_{fm} = \frac{1}{L}\int_0^L T_f\,(x)dx$$

which on substituting terms by relevant gives

$$T_{fm} = T_i + \left(\frac{\eta I_0}{U_tF_R}\right)\left[1 - \left(\frac{F_R}{F'}\right)\right] \qquad (10)$$

2.2 Double Glazing Solar air heater

The steady state energy balance conditions for the various parts of conventional flat plate solar air collector is given as

$$I_o\tau^2\alpha = U_t\left(T_{pm} - T_a\right) + h_1\left(T_{pm} - T_f\right) + h_r\left(T_{pm} - T_{bm}\right) \qquad (1)$$

$$h_r\left(T_{pm}-T_{bm}\right)=h_2\left(T_{bm}-T_f\right) \qquad (2)$$

$$\frac{m'C_p}{B}\frac{dT_f}{dx}=h_1\left(T_{pm}-T_f\right)+h_2\left(T_{bm}-T_f\right) \qquad (3)$$

Where, $h_r=\frac{4\sigma T_{av}^3}{\frac{1}{p}+\frac{1}{b}-1}$

Solving these equations we get

$$F'=1+\left(1+\frac{U_t}{h_e}\right)^{-1} \qquad (4)$$

$$F_R=\frac{m'C_p}{U_tA_p}\left[1-\exp\left\{-\frac{F'U_tA_p}{m'C_p}\right\}\right] \qquad (5)$$

$$Q_u=F_RA_p[I_0\tau^2\alpha-U_t(T_i-T_a)] \qquad (6)$$

$$\eta=\frac{Q_u}{I_0A_p} \qquad (7)$$

$$T_o=\left[Q_u/\left(C_pm'\right)\right]+T_i \qquad (8)$$

$$T'_{pm}=T_a+\left[\frac{I_0}{U_t}(\tau^2\alpha-\eta)\right] \qquad (9)$$

$$T_{fm}=T_i+\left(\frac{\eta I_0}{U_tF_R}\right)\left[1-\left(\frac{F_R}{F'}\right)\right] \qquad (10)$$

2.3 Double Pass Solar air heater with internal fins

The steady state energy balance conditions for the various parts of conventional flat plate solar air collector is given as

$$I_0\tau^2\alpha=h_1\Theta\left(T_{pm}-\ T_f\right)+U_t\left(T_{pm}-T_a\right) \qquad (1)$$

$$\frac{m'(1+R)C_p}{B}\frac{dT_f}{dx}=h_1\Theta B\left(T_{pm}-T_f\right) \qquad (2)$$

Where

$$\square=1+\left(A_f\eta_f-A_{fb}\right)/A_p \qquad (3)$$

$$\eta_f=\tanh(Mw_2)/Mw_2 \qquad (4)$$

And,

$$M=\sqrt{h_1(2L+2t)/K_sLt} \qquad (5)$$

Solving these equations we get

$$F'=\frac{h_1\Theta}{h_1\Theta+U_t} \qquad (6)$$

$$F_R=\left[\frac{m'(1+R)C_p}{U_tA_p}\right]\left\{1-\exp\left[-\frac{F'U_tA_p}{m'(1+R)C_p}\right]\right\} \qquad (7)$$

$$Q_u=\frac{F_RA_p[\tau^2\alpha I_0-U_t(T_i-T_a)]}{1+\left(\frac{F_RU_tA_p}{m'C_p}\right)\left[\frac{R}{(1+R)}\right]} \qquad (8)$$

$$\eta=\frac{Q_u}{I_0A_p} \qquad (9)$$

$$T_0=T_i+\left(\eta I_0A_p/m'C_p\right) \qquad (10)$$

Mean fluid temperature is calculated by using the formula

$$T_{fm}=\frac{1}{L}\int_0^L T_f(x)dx$$

which on substituting terms by relevant gives

$$T_{fm}=T_i+[R(1+R)]\left(\frac{I_0A_p\eta}{m'C_p}\right)+\left(\frac{\eta I_0}{U_tF_R}\right)\left[1-\left(\frac{F_R}{F'}\right)\right] \qquad (11)$$

$$T'_{pm}=T_a+\left[\frac{I_0}{U_t}(\tau^2\alpha-\eta)\right] \qquad (12)$$

2.4 Empirical relations

For calculating the above parameters we need to find out the overall heat transfer coefficients and dimensionless numbers such a Reynolds number and Nusselt number.

An empirical equation for the loss coefficient from the top of solar collector to the ambient U_t was developed by Klein

Nomenclature

		h_w	Convective heat transfer coefficient between glass cover and ambient, W/m^{2}K
A_p	Surface area of the absorbing plate,m^2	h_1	Convective heat transfer coefficient between the absorber plate and the air stream, W/m^2
A_f	Total surface area of fins,m^2	h_2	Convective heat transfer coefficient between the bottom plate and the air stream, W/m^2
A_{fb}	Total cross-sectional area of fins,m^2	L	Length of collector, m
B	Width of the air tunnel in the solar collector, m	I_0	Intensity of solar radiation, W/m^2
C_p	Specific heat of air at constant pressure, J/kgK	K_s	Thermal conductivity of material of fins, W/mK
D_e	Equivalent diameter of the air tunnel, m	T_a	Ambient temperature, K
F'	Efficiency factor of the solar air heater	m'	Mass flow rate, m/s
F_R	Heat removal factor for the solar air heater	N	Total number of fins
H	Height of the air tunnel in the solar air collector, m	Nu	Nusselt number
R	Remixing ratio	T_{fm}	Mean fluid temperature, K
Re	Reynolds number	T_i	Inlet air temperature, K
T	Thickness of fin, m	T_{bm}	Mean bottom plate temperature, K
U_t	Loss coefficient from the top of absorbing plate to the atmosphere, W/m^{2}K	T_{pm}	Assumed mean temperature of absorber plate, K
w_1	Distance between fins, m	T_0	Fluid outlet temperature, K
w_2	Height of fins, m	Q_u	Useful heat gain per unit time, W
V	Wind velocity, m/s	ε_p	Emissivity of absorber plate
X	Axis along the flow direction, m	ε_b	Emissivity of bottom plate
η	Efficiency of solar air collector	η_f	Fin efficiency
P	Density of air, kg/m^3	σ	Stefan Boltzman Constant
τ	Transmittance of glass cover	θ	Dimensionless quantity

A	Absorptivity of the absorbing plate	μ	Absolute viscosity of fluid , Ns/m^2
T_{pm}'	Calculated value of mean absorber plate temperature, K	T	Difference between assumed and calculated values of mean absorber plate temperature, K

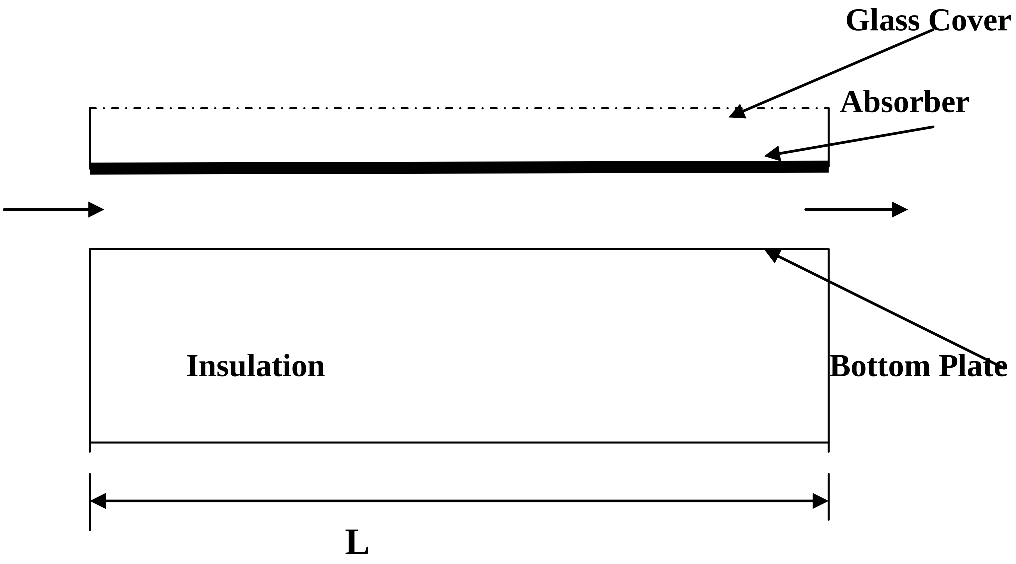

Figure1: Conventional Solar Air Heater

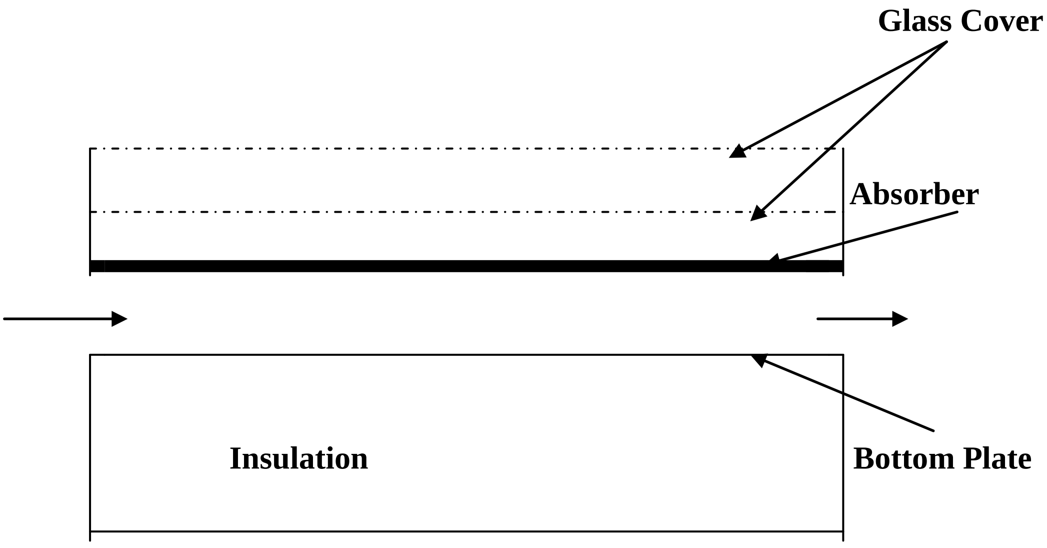

Figure2: Double glazing solar air heater

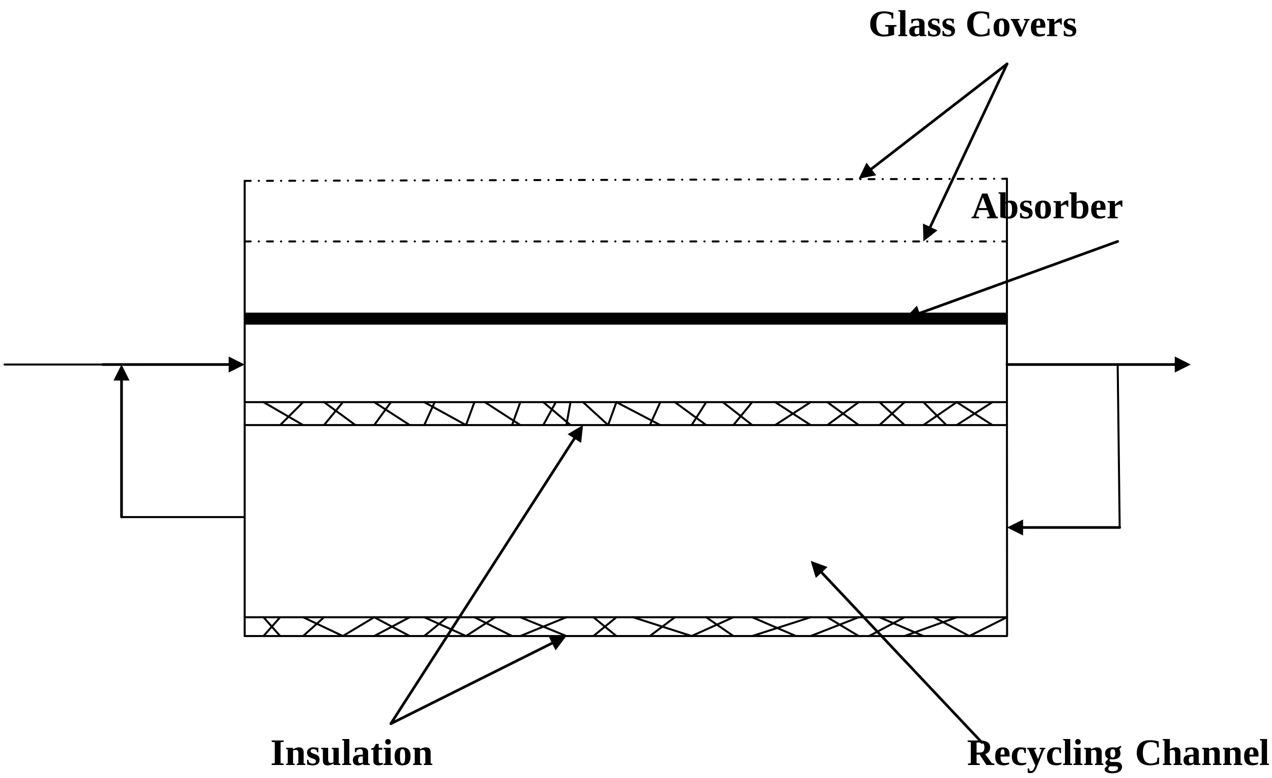

Figure3: Double pass solar air heater with internal fins

[14] following the basic procedure of Hottel and Woertz [5] ,

$$U_t = \left\{ \frac{2\left(T_{pm}/520\right)}{\left[\frac{T_{pm}-T_a}{2+f}\right]^{0.43\left(1-\frac{1-100}{T_{pm}}\right)}} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma\left(T_{pm}+T_a\right)\left(T_{pm}^2+T_a^2\right)}{\left(_p + 2 * 0.00591 h_w\right)^{-1} + \left[2 * 2 + f - 1 + 0.133_p\right]/_g - 2} \tag{1}$$

Where,

$$\mathrm{f} = \left(1 + 0.089\mathrm{h}_{\mathrm{w}} - 0.1166\mathrm{h}_{\mathrm{wp}}\right)(1 + 0.07866 * 2) \tag{2}$$

The convective heat transfer coefficient h_w for air flowing over the outside surface of the glass cover depends primarily on the wind velocity. V. McAdams [15] obtained experimental result as

$$\mathrm{h}_{\mathrm{w}} = 5.7 + 3.8\mathrm{V} \tag{3}$$

Reynolds number is calculated by using the following relation

$$\mathrm{Re} = \frac{2\mathrm{m}'(1+\mathrm{R})}{\mu(\mathrm{B}+\mathrm{H})} \tag{4}$$

And, Nusselt number is calculated by using following relation

$$\mathrm{Nu} = 0.0158\mathrm{Re}^{0.8} \tag{5}$$

3. Computational Solution

The whole analysis is carried out with the help of **MATLAB R2009b**. **MATLAB** is a software package for high-performance numerical computation and visualization. It provides an interactive environment with hundreds of built-in functions for technical computation, graphics and animation. It also provides easy extensibility with its own high-level programming language. The name MATLAB stands for MATrix LABoratory.

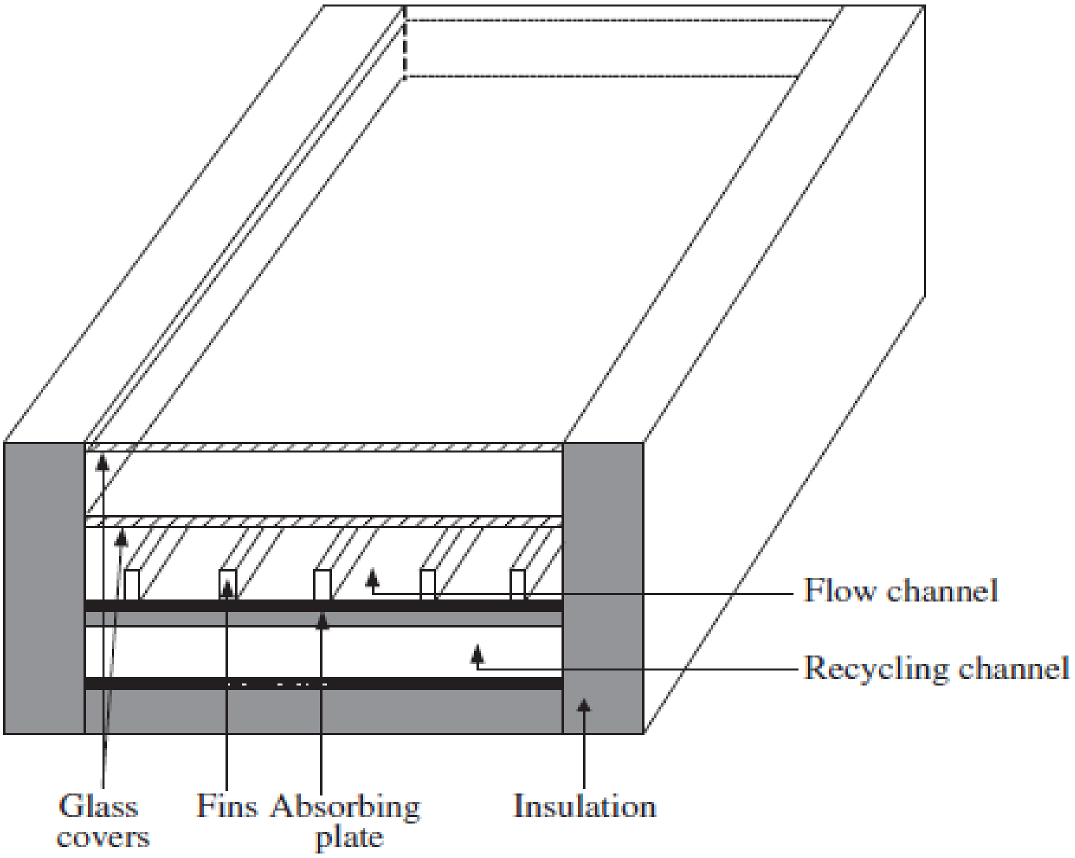

Figure4: Schematic diagram of double pass internally finned solar air heater

Input Parameters

S.No.	Input Parameter	Magnitude
1	Width of the air tunnel, m	0.6
2	Length of the collector, m	0.6
3	Thermal conductivity of fin, W/mK	386
4	Mass flow rate, m/s	0.01, 0.015, 0.02
5	Solar radiation intensity, W/m^2	950, 1100
6	Thickness of fin, m	0.001
7	Emissivity of glass cover	0.94
8	Emissivity of absorber plate	0.95
9	Absorptivity of absorbing plate	0.95
10	Transmittance of glass cover	0.0875
11	Stefan Boltzmann Constant, W/m^{2}K^4	5.67×10^{-8}
12	Air velocity, m/s	1
13	Height of fins, m	0.013
14	Distance of fins, m	0.025
15	Ambient temperature, K	283
16	Number of fins	24

3.1 Algorithms

The MATLAB programme algorithm with respective notations and formulae for the three types of solar air heaters described above are given below. Algorithm is the step by step indication of execution of any program. Algorithm is very essential to understand the flowchart of any programme.

3.1.1Algorithm for the MATLAB programming of Conventional and Single pass double glazing solar air heaters

1) START
2) Assume any arbitrary value of T_{pm}.
3) Enter input value of C_p, μ, K, T_i , I_o, H, K_s, B, W_1, W_2, t, n, V, τ, α, ε_p, ε_g
4) Set initial value of m' =0.01
5) Find out the value of required parameters (U_t , F', F_R , Q_u) and hence the value of u, v and T . Here u= { m',T_{pm}',T_o, η}, v={m'} and T=T_{pm}-T_{pm}'
6) If value of T lies in the range of {-1,1} then display the value of u as optimized otherwise display the value of v as not optimized
7) Increase value of m' by 0.005, if value of m' is less than 0.03 go to STEP 4.
8) When the whole loop is completed notice the values which are not optimised to find such values again go to step 2 and repeat the whole steps further until all of the values get optimised.
9) END

3.1.2Algorithm for the MATLAB programming of Double pass internally finned solar air heater

1) START
2) Assume any arbitrary value of T_{pm}.
3) Enter input value of C_p, μ, K, T_i , I_o, H, K_s, B, W_1, W_2, t, n, V, τ, α, ε_p, ε_g
4) Set initial value of m' =0.01
5) Set initial value of R=1 .
6) Find out the value of required parameters (U_t , F', F_R , Q_u) and hence the value of u, v and T . Here u= { m',T_{pm}',T_o, η}, v={m'} and T=T_{pm}-T_{pm}'
7) If value of T lies in the range of {-1,1} then display the value of u as optimized otherwise display the value of v as not optimized
8) Increase value of R by 1 , if value of R is less than 3 go to STEP 5 else go to NEXT STEP.
9) Increase value of m' by 0.005, if value of m' is less than 0.03 go to STEP 4.
10) When the whole loop is completed notice the values which are not optimised to find such values again go to step 2 and repeat the whole steps further until all of the values get optimised.
11) END

3.1 Flow charts

Flow charts for the MATLAB programming for the three types of solar air heaters are illustrated below. The first flow chart corresponds to conventional and single pass double glazing solar air heater while the second one corresponds to double pass internally finned solar air heater.

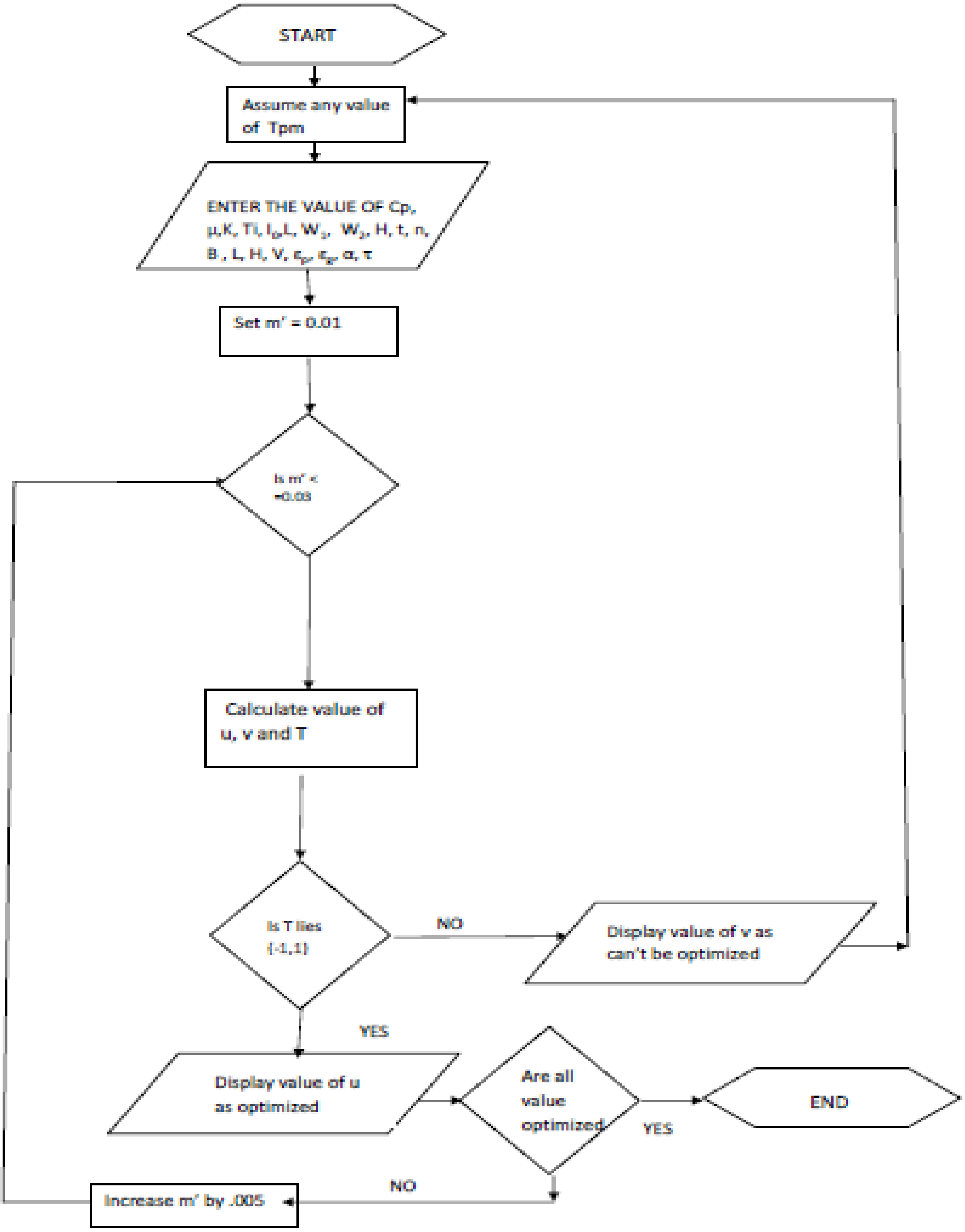

Figure5: Flow Chart for the Conventional and single pass double glazing solar air heaters

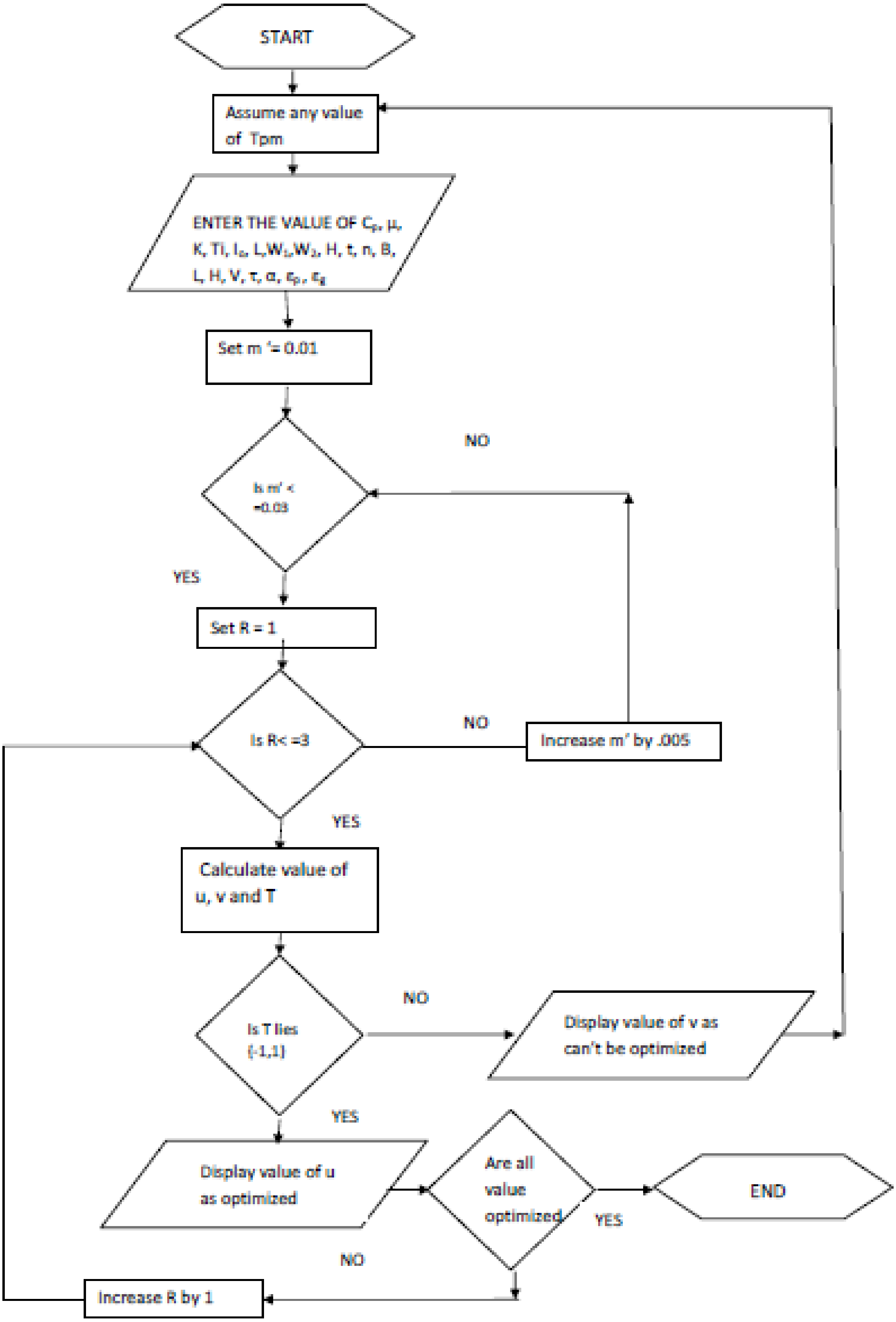

Figure6: Flow Chart for the Double pass internally finned solar air heater

4. Results and Discussions

The effects of the air inlet temperature and incident solar radiation on the collector efficiency of the conventional, double glazing single pass and double pass solar air heaters with the fins attached have been investigated computationally. As evident from the results, it is clear that the efficiency of all the three types of solar air heaters increases with the increase in mass flow rate and decreasing fluid inlet pressure. The remixing ratio also has a tremendous effect on the efficiency of double pass finned solar air heater and the efficiency increases with the increase in the value of remixing ratio R. Similarly it is clear from the results obtained that the value of mean absorber plate temperature T_{pm} and fluid outlet temperature T_o decreases with the increase in mass flow rate.

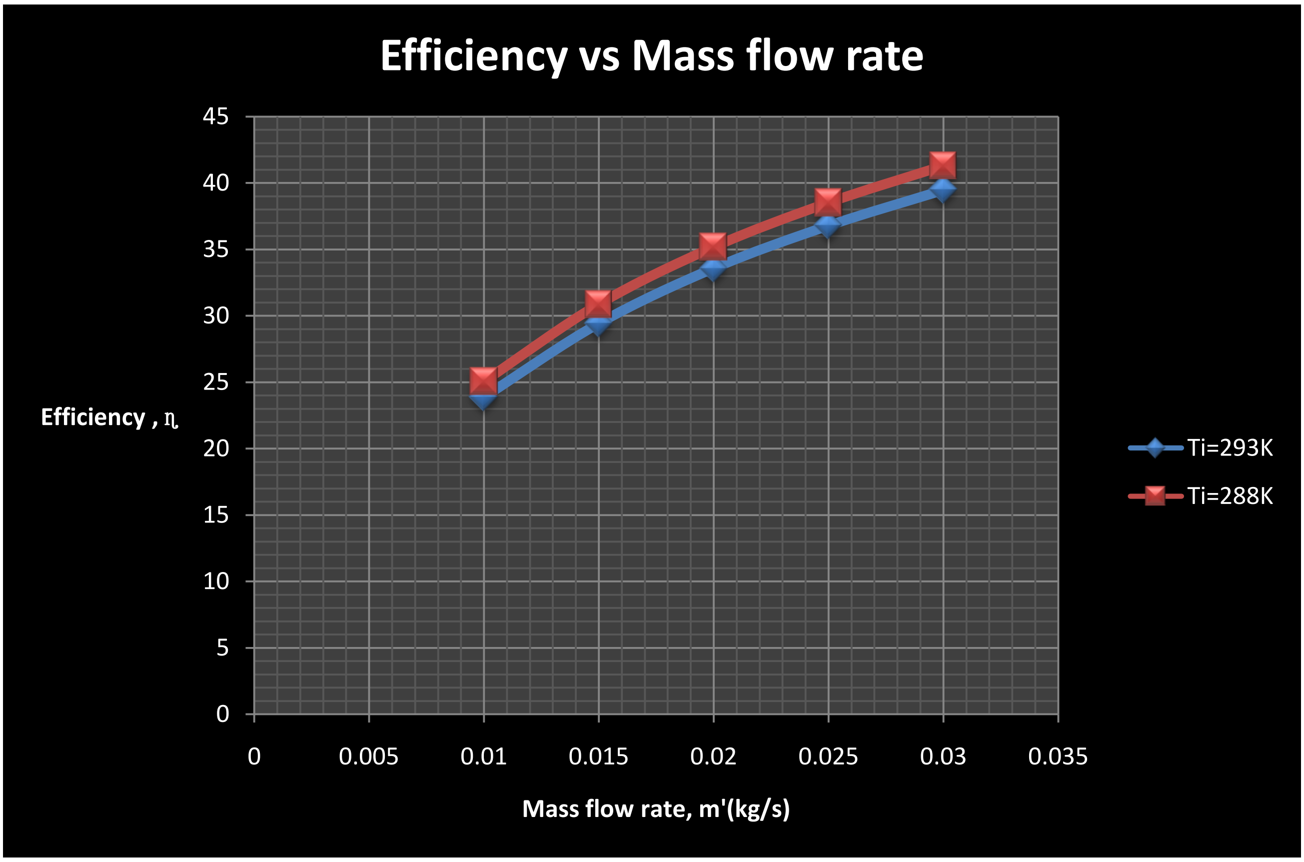

Figure7: Graph of conventional solar air heater for I_o=950W/m^2

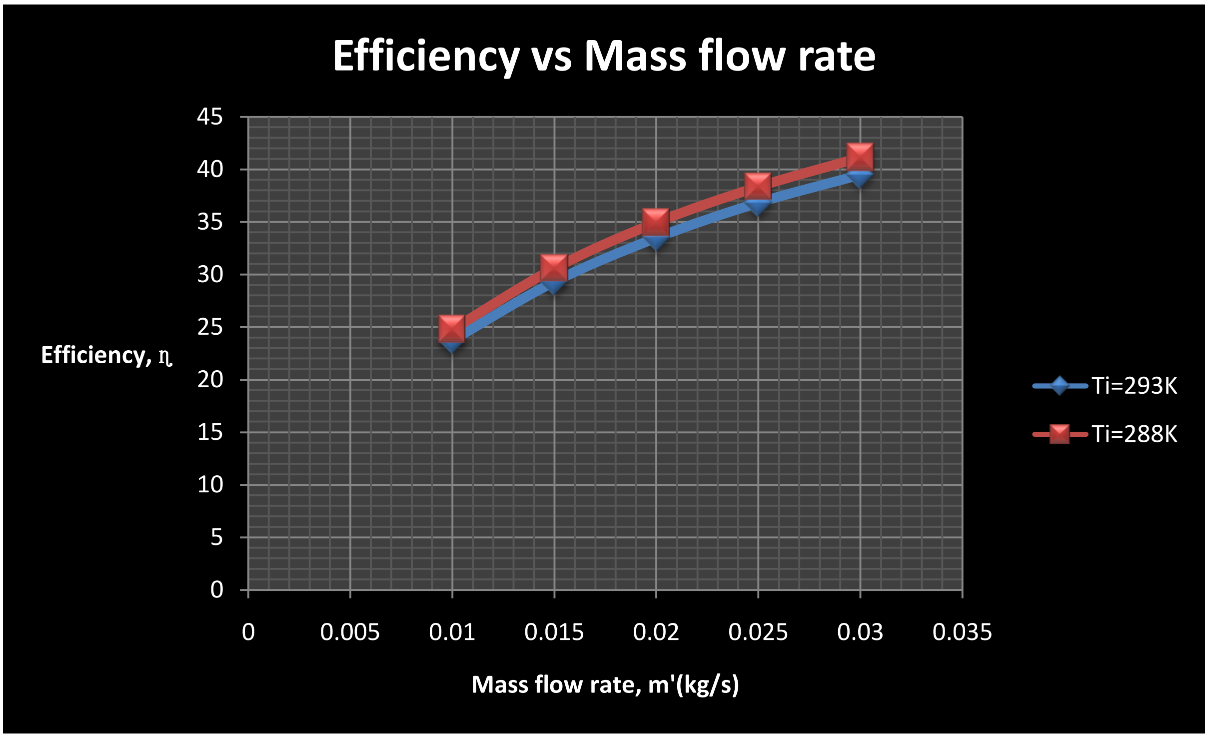

Figure8: Graph of conventional solar air heater for I_{-0} = 1100 W/m^2

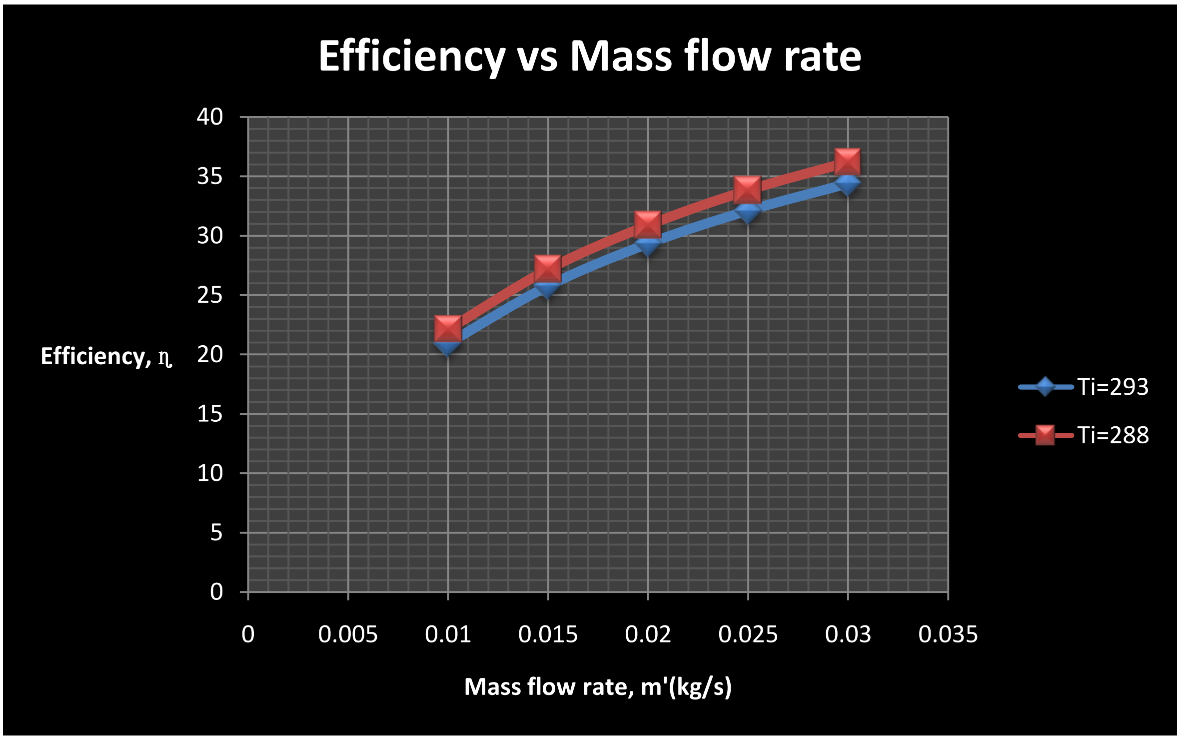

Figure9: Graph of double glazing single pass solar air heater for I_0=950 W/m^2

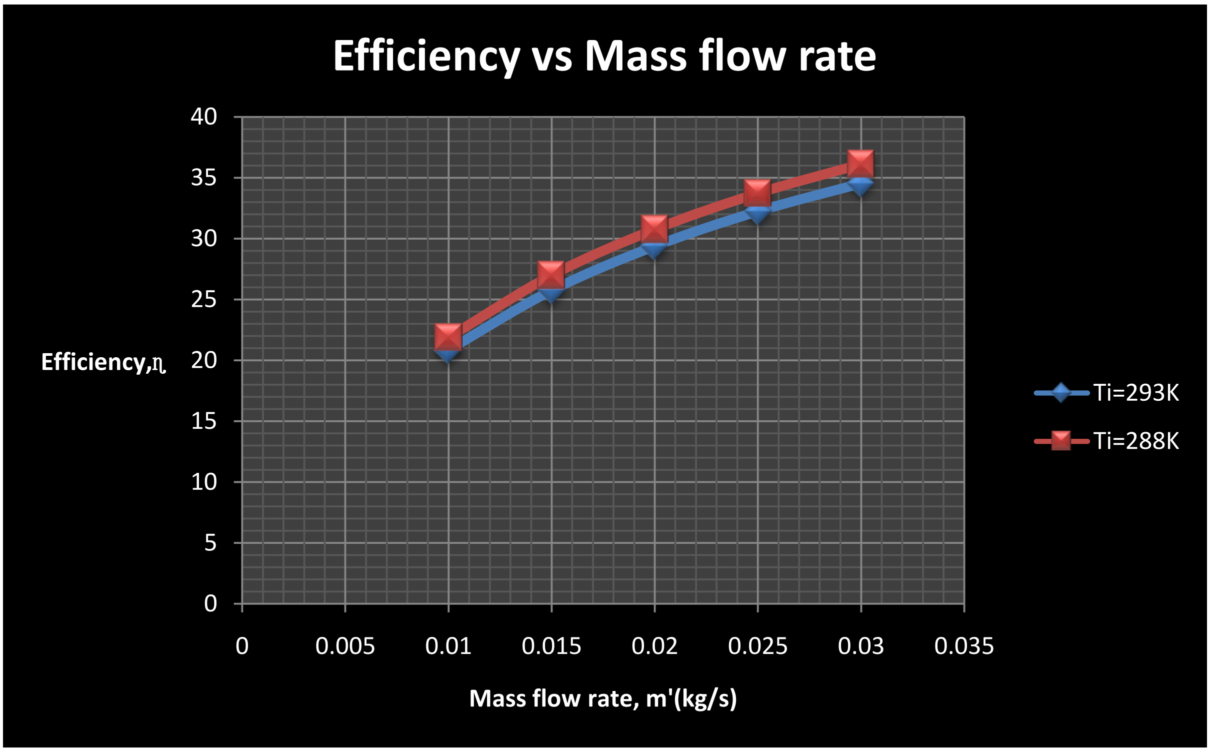

Figure10: Graph of double glazing single pass solar air heater for I_0=1100 W/m^2

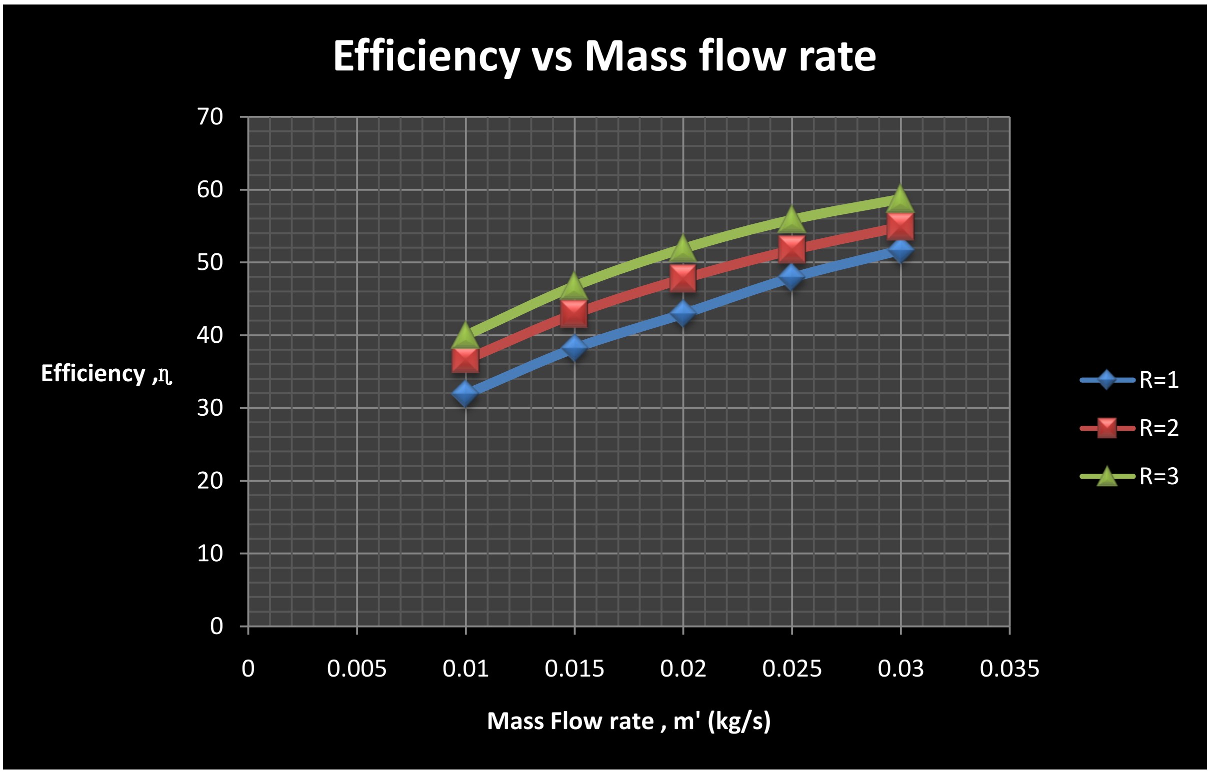

Figure11: Graph of double pass finned solar air heater for I_o=950W/m^2 and T_i=288 K

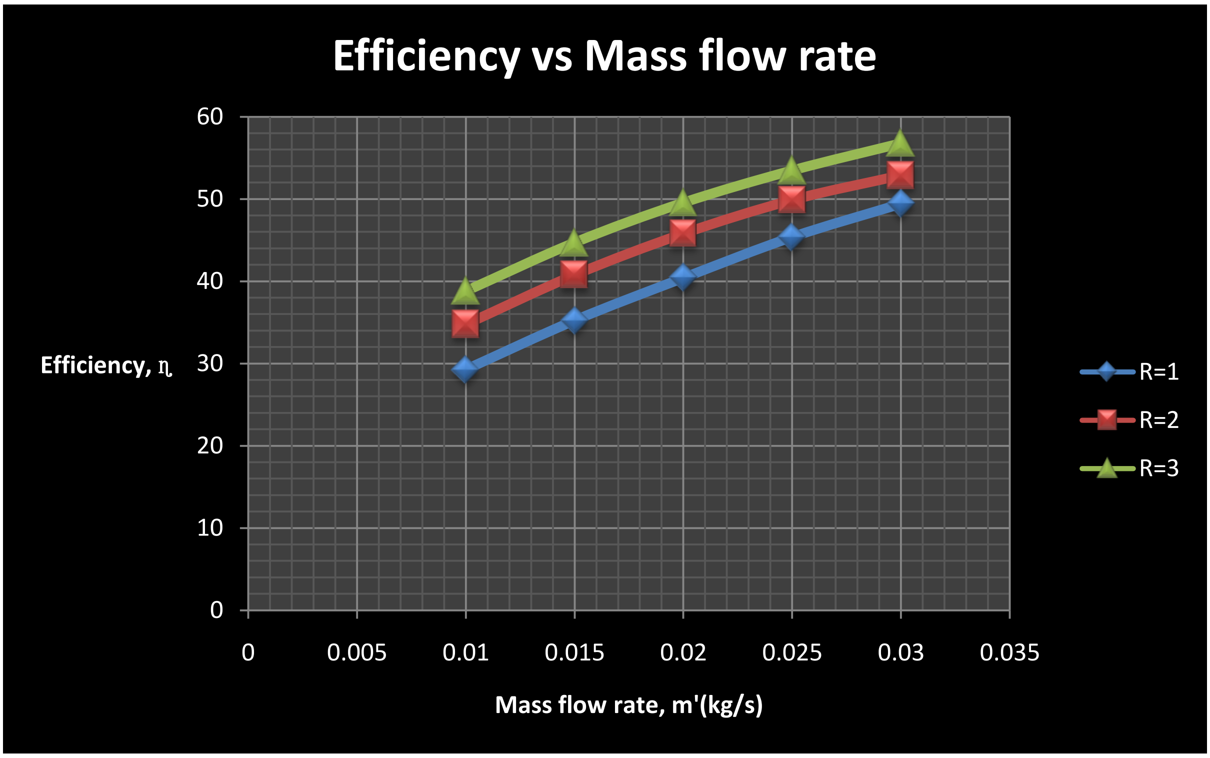

Figure12: Graph of double pass finned solar air heater for I_o= 950 W/m^2 and T_i = 293K

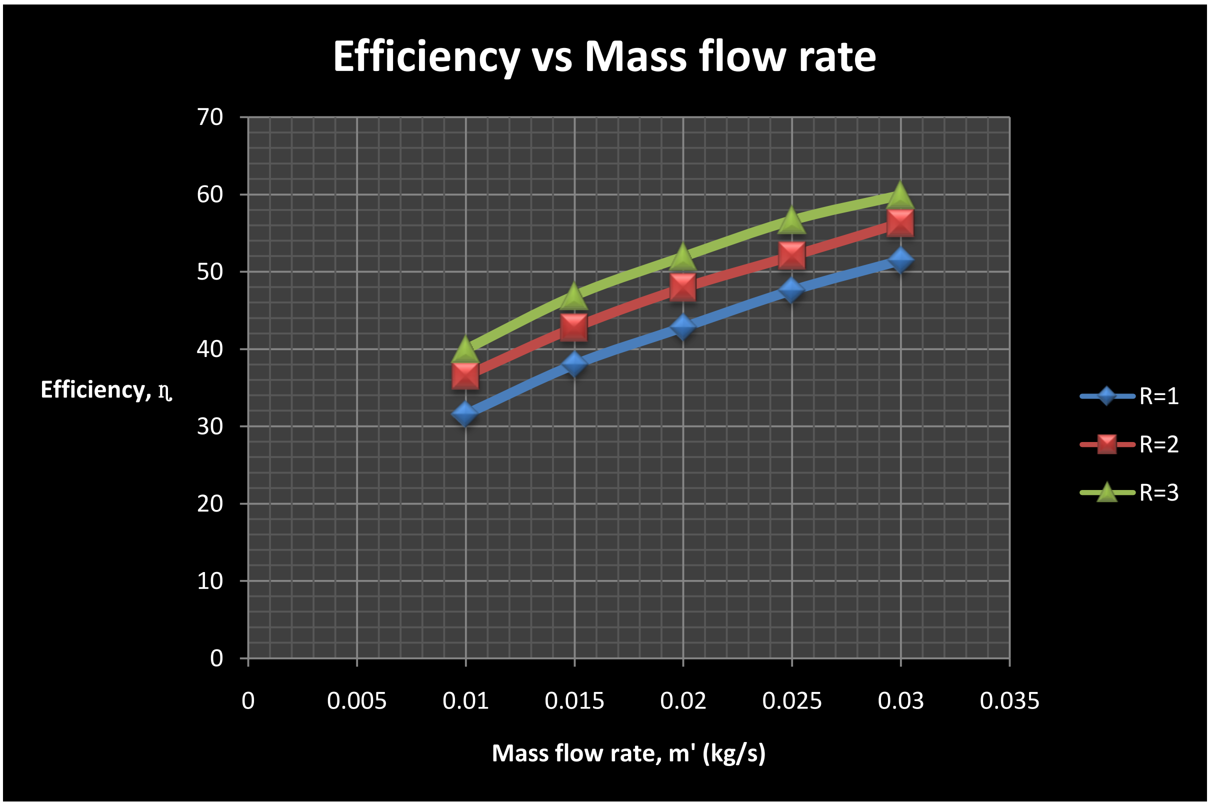

Figure13: Graph of double pass finned solar air heater for I_o= 1100 W/m^2 and T_i = 288K

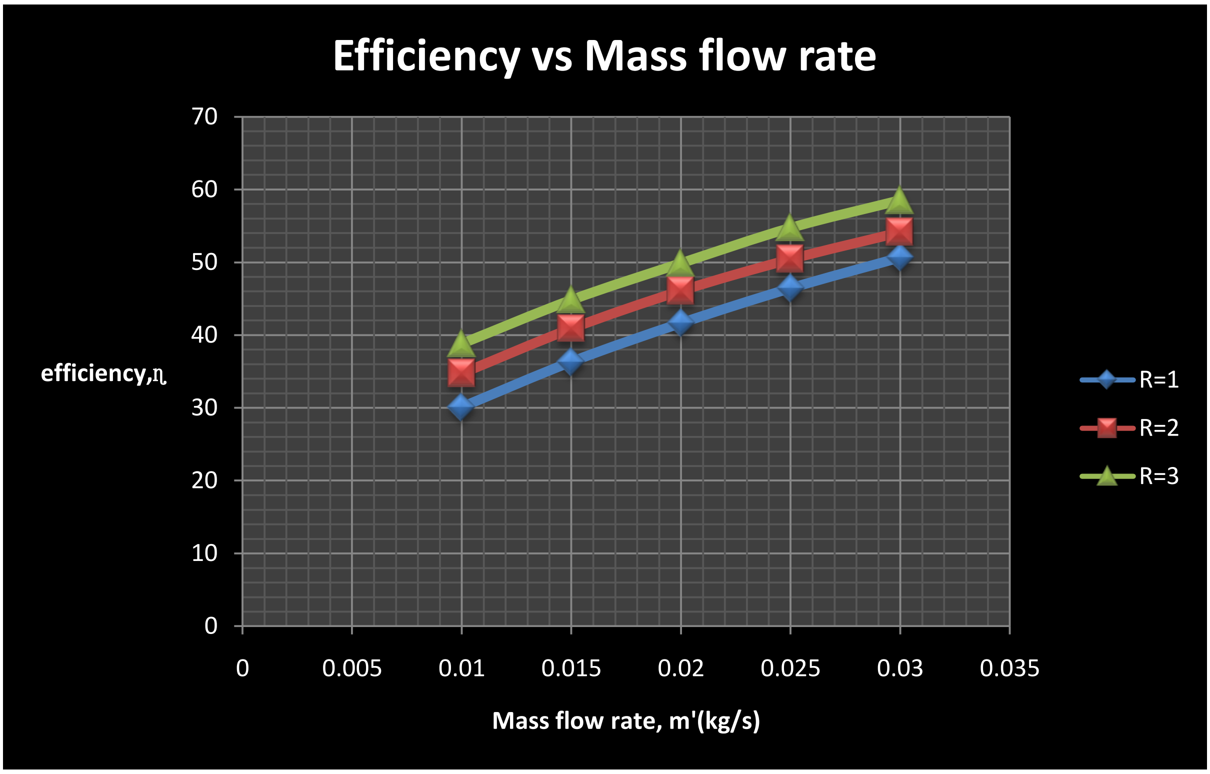

Figure14: Graph of double pass finned solar air heater for I_o=1100W/m^2 and T_i=293K

The improvement of collector performance for Conventional solar air heater

S.NO	I_o= 950W/m^2					I_o= 1100W/m^2		
	T_i (K)	m' (kg/s)	ɳ (%)	T_{pm}(K)	T_o(K)	ɳ (%)	T_{pm} (K)	T_o (K)
1	293	0.01	23.88	366.54	301.08	23.75	376.79	302.29
2		0.015	29.43	360.29	299.64	29.32	369.69	300.66
3		0.02	33.58	355.57	298.69	33.50	364.30	299.56
4		0.025	36.79	351.59	297.98	36.84	360.14	298.78
5		0.03	39.47	348.56	297.45	39.50	356.47	298.16
6	288	0.01	25.04	365.19	296.47	24.77	375.48	297.69
7		0.015	30.86	358.75	294.97	30.59	368.21	295.98
8		0.02	35.17	353.73	293.96	34.96	362.72	294.85
9		0.025	38.51	349.52	293.21	38.36	358.12	294.02
10		0.03	41.29	346.29	292.61	41.15	354.44	293.38

The improvement of collector performance for double glazing solar air heater

S.NO	I_o= 950W/m^2					I_o= 1100W/m^2		
	T_i (K)	m' (kg/s)	η (%)	T_{pm}(K)	T_o(K)	η (%)	T_{pm} (K)	T_o (K)
1	293	0.01	20.94	358.06	300.09	20.84	367.16	301.16
2		0.015	25.77	352.52	298.82	25.73	361.06	299.72
3		0.02	29.33	348.19	297.97	29.37	356.28	298.76
4		0.025	32.11	344.69	297.35	32.23	352.43	298.05
5		0.03	34.39	341.89	296.89	34.53	349.19	297.52
6	288	0.01	22.12	356.87	295.49	21.88	366.03	296.57
7		0.015	27.17	350.93	294.14	26.98	359.52	295.05
8		0.02	30.89	346.30	293.23	30.75	354.45	294.03
9		0.025	33.84	342.73	292.59	33.71	350.36	293.29
10		0.03	36.21	339.74	292.09	36.10	346.94	292.72

The improvement of collector performance for double pass finned solar air heater for R=1

S.NO	I_o= 950W/m^2					I_o= 1100W/m^2		
	T_i (K)	m' (kg/s)	η (%)	T_{pm}(K)	T_o(K)	η (%)	T_{pm} (K)	T_o (K)
1	293	0.01	29.26	347.03	303.17	30.11	355.03	304.81
2		0.015	35.23	339.49	301.19	36.32	346.79	302.50
3		0.02	40.41	334.01	299.85	41.63	337.36	300.38
4		0.025	45.38	330.51	297.67	46.42	334.86	298.59
5		0.03	49.43	327.06	295.28	50.64	331.52	296.84
6	288	0.01	31.88	345.04	298.81	31.56	353.08	300.38
7		0.015	38.19	337.09	296.63	37.99	344.31	297.94
8		0.02	42.93	331.24	295.22	42.81	337.76	296.33
9		0.025	47.89	227.74	294.59	47.57	333.67	295.17
10		0.03	51.67	224.96	293.61	51.45	330.18	294.76

The improvement of collector performance for double pass finned solar air heater for R=2

S.NO	I_o= 950W/m^2					I_o= 1100W/m^2		
	T_i (K)	m' (kg/s)	η (%)	T_{pm}(K)	T_o(K)	η (%)	T_{pm} (K)	T_o (K)
1	293	0.01	34.77	341.52	304.79	34.72	348.86	306.62
2		0.015	40.78	333.64	302.22	40.89	340.05	303.71
3		0.02	45.81	328.21	300.59	46.08	333.93	301.86
4		0.025	49.87	324.47	298.54	50.43	327.63	299.75
5		0.03	52.87	321.37	296.31	54.14	324.18	297.81
6	288	0.01	36.60	339.13	300.41	36.51	346.66	302.28
7		0.015	42.91	330.85	297.71	42.78	337.30	299.20
8		0.02	47.73	325.13	295.99	47.89	330.83	297.25
9		0.025	51.67	321.56	293.60	52.04	326.71	295.75
10		0.03	54.87	318.34	291.21	56.31	323.49	293.62

The improvement of collector performance for double pass finned solar air heater for R=3

S.NO	I_o= 950W/m^2					I_o= 1100W/m^2		
	T_i (K)	m' (kg/s)	η (%)	T_{pm}(K)	T_o(K)	η (%)	T_{pm} (K)	T_o (K)
1	293	0.01	38.79	337.72	305.82	38.82	344.62	307.84
2		0.015	44.69	329.78	302.88	44.83	335.60	304.48
3		0.02	49.54	324.47	301.07	49.88	329.77	302.38
4		0.025	53.46	320.73	299.56	54.74	325.63	300.65
5		0.03	56.76	317.21	297.87	58.54	322.93	298.23
6	288	0.01	39.94	335.07	301.48	39.94	342.03	303.52
7		0.015	46.73	326.74	298.39	46.88	332.68	300.12
8		0.02	51.89	321.16	296.48	51.93	326.26	297.81
9		0.025	55.86	317.76	294.45	56.64	324.45	295.24
10		0.03	58.71	314.86	292.86	59.89	321.84	293.62

Conclusion

From the analysis of various types of solar air heaters viz conventional , double glazing single pass and double pass finned solar air heaters, it is concluded that for the same mass flow rate, double pass finned solar air heater is having the highest efficiency.

References

[1]Choudhury. C, Chauhan P. M. and Garg H.P. Performance and Cost Analysis of Two-Pass Solar Air Heaters, Heat Recovery System and CHP, 15 (1995) No. 8, pp. 755-773.

[2] Duffie, J.A. and Beckman, W.A., Solar Engineering of Thermal Processes, (Toronto, John Wiley 1991.)

[3] Fudholi A, Ruslan MH, Sopian K, Supranto. Review of multi-pass solar air collectors with heat transfer surface enhancement. Proceedings of the 4th Scientific Conference PPI-UKM. 2009. p. 3-11.

[4] Fudholi A. Sopian K, Ruslan MH, Alghoul MA, Sulaiman MY. Reviev of solar dryers for agricultural and marine products. Renewable & Sustainable Energy Review 2010;14:1-30.

[5] H.C. Hottel, B.B.Woertz, Performance of flat-plate solar-heat collector, Transactions of the American Society of Mechanical Engineers 64 (1942) 91–104.

[6] Helal, O., B. Chaouachi, S. Gabsi and C. Bouden, 2010. Energetic performances study of an integrated collector storage solar water heater. Am. J. Eng. Applied Sci., 3: 152-158. DOI: 10.3844/ajeassp.2010.152.158

[7] Ho CD, Yeh CW and Hsieh SM. Improvement in device performance of multi-pass flat-plate solar air heaters with external recycle. Renewable Energy 2005;30: 1601-21.

[8]Karim M.A., Hawlader M.N.A. Development of Solar Air Collectors for Drying Applications. Energy Conversion and Management, 45 (2004) pp 329-344.

[9] Pradhapraj, M., V. Velmurugan and H. Sivarathinamoorthy, 2010. Review on porous and nonporous flat plate air collector with mirror enclosure. Int. J. Engineer. Sci. Technol., 2: 4013-4019.

[10]Ratna Verma, Ram Chandra and H. P. Garg, Parametric Studies on the Corrugated Solar Air Heaters With and Without Cover, Renewable Energy, 1 No.3/4 (1991) pp. 361-371

[11] Ratna Verma, Ram Chandra and H. P. Garg. Technical note- Optimization of Solar Air Heaters of Different Designs, Renewable Energy, 2 (1992) No.4/5, pp.521-531

[12] Reda, S.M., 2010. Photostability of ponceau 2r doped thin film sol-gel silica as luminescent solar collector. Energy Res. J., 1: 36-41. DOI: 10.3844/erjsp.2010.36.41

[13] Sopian, K., M.A. Alghoul, E.M. Alfegi, M.Y. Sulaiman and E.A. Musa, 2009. Evaluation of thermal efficiency of double-pass solar collector with porous-nonporous media. Renewable Energy., 34: 640-645. DOI: 10.1016/j.renene.2008.05.027

[14] S.A. Klein, Calculation of flat-plate loss coefficients, Solar Energy 17 (1975) 79–80.

[15] W.H. McAdams, Heat Transmission, McGraw-Hill, New York, 1954.