International Journal of Advance Research and Innovation
Vol. 1(2), Apr-Jun 2013, pp. 71-78
Doi: 10.51976/ijari.121315
www.gla.ac.in/journals/ijari

Article Info
Received: 01 Aug 2013 | Revised Submission: 22 Aug 2013 | Accepted: 28 Aug 2013 | Available Online: 20 Sept 2013

Evaluation of Thermal Performance of Low Cost Plastic Collectors for Rural Applications

*R. S. Mishra**

ABSTRACT

Energy is a critical input in the national development process. In fact, it is the basic requirement for human life, agriculture, industry, transportation, communication and many other economic activities of the present civilization. In the present day, the depleting fossil fuels in the various countries, the terms of energy crises underlines the need of paying serious attention to the effective /efficient utilization of existing conventional and non conventional energy sources in terms of energy conservation through effective management for maximum agricultural production.

In this paper, experimental studies on solar air/water heating cum storage systems using low cost plastic films have been carried out and periodic thermal model has been proposed. Explicit expressions have been obtained for air and absorber temperatures. The utility of the thermal model was established by conducting experiments on various systems for several days. Closed agreement between theoretical and experimental results validates the proposed methodology.

Keywords: *Plastic Technology Flow Through The Porous Medium; Solar Air Heaters Thermal Energy Storage Systems.*

1.0 Introduction

The environmental degradation has added new problem more particularly in the developing countries because developing countries are facing serious environmental problems and energy cries because of the negative effects of the developing economies and due to fast depletion of bio-mass and other resources and from the conditions of poverty and under development. The development can take place at the cost of environment only until a point in fact, development without concern for environment can only a short time development. In the long run, it can only be anti-development and can go on only at the cost of enormous human suffering which increases poverty.

Energy crises due to environment degradation are imposing serious problems for the better survival of rural population. To overcome the energy crises and provide the optimal mix energy in terms of hybrid energy optimization option in both conventional and non-conventional energy sources through integration in terms of useful thermal energy demand (i.e. fraction of thermal energy demand replace by solar energy.

2.0 Application of low Cost Plastic Collectors

The applications of porous materials in the construction of the solar energy plastic collectors are well known. The heat transferred in the porous absorber is subjected to the solar radiation is highly effective in the heating of working air and improving thermal efficiency.

For porous air heating plastic collectors, the blackened textile polyester cloth of porous materials having longer life in comparison to the ordinary cloth and very light in weight has been used as solar radiation absorber for reducing heat losses to the environment.

The glass covers of air heaters are replaced by low cost thermal conductivity polythene plastic covers.

These combinations are cost effective and very light in weight and required very low fan power for blowing the air through air heating collectors.

**Corresponding Author: Department of Mechanical Engineering, Delhi Technological University, New Delhi, India (E-mail: professor_rsmishra@yahoo.co.in)*

3.0 Experimental Investigations

The plastic collectors are chosen for experimental study are flexible type in which a porous black textile cloth acts as a porous absorber. The edges of absorber are attached to two transparent plastic sheet of ultraviolet stabilized polyvinyl chloride (PVC) covering it from the both sides. Mishra .(1984) developed a dimensionless thermal steady state analysis to find out the effect of various boundary conditions applicable in the analysis of a matrix air heaters made of plastic films with textile cloth of 100% polyester have been used as a porous absorber and compared thermal performance in terms of rise in the temperature difference and thermal efficiency and also compared with the ratio of outlet air temperature to the inlet air temperature for two mass flow rates and observed optimum thickness of matrix absorber as 0.00720 m. Mishra. (1992) had obtained the steady state analytical solutions for temperature distributions in the porous collectors and considered the two cases of (i) air flow from top to bottom and (ii) bottom to top side and observed that , when outlet hot air comes in contact with cover at the top side of the porous absorber air heating collector ,looses significantly heat energy to the ambient air which causes the decreasing thermal efficiency around 15%.In this paper, we developed simple periodic thermal model for finding actual thermal performance of low cost plastic collectors under varying metrological conditions and closed agreement between theoretical results and experimental measurements have been observed which proves the validity of proposed thermal model for low temperature porous air heating plastic collectors for rural domestic applications specially fruits and vegetable drying applications at the minimum cost.

Mathematical Modeling of Porous and Non Porous Absorber Solar Air Heating Collectors

Periodic thermal model of low cost plastic porous matrix collector

The analysis of porous plastic air heating collector cum storage systems have been performed under following mode of operation.

Different absorber & fluid temperatures

In the configuration of the porous air heater, in which the performance of the system depends upon collector parameters. The energy balance equation for the absorber temperature over the segment of Thickness dX can be written as:

$$h_v\left(\mathrm{T_f}(X,t)-T_m(X,t)\right)+K_e\left(\frac{d^2\mathrm{T_m}(X,t)}{dX^2}\right)-\frac{dQ}{dX}=\rho_m C_{pm}\left(\frac{dT_m(X,t)}{dt}\right) \quad (1)$$

Where Tf (x,t) is the local air temperature & dI/dx is the heat energy attained by the surfaces. The first term in the equation represents the heat retained in the absorber while second term is for the heat transfer from the hot air to the porous absorber. The third term represents the energy stored by the porous absorber. The absorber temperature is however related to air temperature by the following expression

$$-\beta \dot{m}_c c_{pf}\left(\frac{d\mathrm{T_f}(X,t)}{dX}\right)=h_v\left(\mathrm{T_f}(X,t)-T_{mi}(X,t)\right) \quad (2)$$

The (-) sign in equation (2) is due to the fact that hot air loses heat to the porous absorber. Correlations relating volumetric heat transfer coefficient to the absorber characteristics into the fluid flow conditions are given by G.O.G.Lof (1948), Farber & Courtier (1982) & Chandra (1981) as follow:

$$h_v = 700\left(\frac{\dot{m}/A_c}{d}\right)^{0.70} \quad (W/(m^3K)) \quad (3)$$

$$d^3T_{fo}(x)/dx^3+a_1d^2T_{fo}(x)/dx^2+a_2dT_{fo}(x)/dx+a_3T_{fo}(x)=-a_3I_{to}$$

Where

$$a_1=(h_v/(m_c/A_c)C_{pf}\beta),\; a_2=(h_v/K_e),\; a_3=-h_v/((m_c/A_c)C_{pf}\beta K_e)$$

$$y_1=\left(-a_3\mu I_{to}\right)/(\mu^3-a_1\mu^2+a_2\mu+a_3)$$

$$y_2(-a_3I_m(n)\mu)/(-\mu^3+a_1\mu^2-a_2\mu+a_4$$

$$a_4=in\omega\rho_m C_{pm}a_3,\; a_5=\exp((-A_cU_lF')/(\dot{m}_c C_{pf}))$$

$$a_6=a_1,\; a_7(n)=-(a_2)+(in\omega\rho_m C_{pm})/K_e)$$

$$a_8(n)=in\omega\rho_m C_{pm}a_3,\; a_9(n)=T_{an}(n)+((\tau\alpha\; I_m(n)/U_L)$$

Rearranging and separating the eqs. Into time dependent & time independent parts one can get solution of differential eqs.

$$T_f=(C_1\exp(\beta_1X)+C_2\exp(\beta_2X+C_3\exp(\beta_3X)+y_1\exp(-\mu X)+$$

$$\mathrm{Real}\sum_{n=1}^{6}(C_4\exp(\beta_4X)+C_5\exp(\beta_5X+C_6\exp(\beta_6X)+y_2\exp(-\mu X)\exp(in\omega t) \quad (5)$$

The following boundary conditions are used

$$-K_m dT_m(d,t)/dX = h_f(T_f(d,t)-T_a(t)) \quad (6)$$

$$\dot{m}C_{pf}(T_{co}(t)-T_f(0,t)) = h_f(T_{co}(t)-T_m(0,t)) \quad (7)$$

$$-K_m dT_m(0,t)/dX = h_f(T_f(0,t)-T_m(0,t)) \quad (8)$$

Assuming periodic nature of solar intensity, ambient temperature, porous absorber temperature & fluidtemperatures. Rearranging eq. (3) we get following third order differential eqs

$$d^3T_{fo}(x)/dx^3 + a_1 d^2T_{fo}(x)/dx^2 + a_2 dT_{fo}(x)/dx + a_3 T_{fo}(x) = -a_3 I_{to} \quad (9)$$

$$d^3T_{fo}(x)/dx^3 + a_6 d^2T_{fn}(x)/dx^2 + a_7 dT_{fn}(x)/dx + a_8 T_{fn}(x) = -a_9 I_{tn} \quad (10)$$

The solution of above eqs.(4, 5) are expressed in the following manner.

$$T_f = (C_1 \exp(\beta_1 X) + C_2 \exp(\beta_2 X + C_3 \exp(\beta_3 X) + y_1 \exp(-\mu X) +$$

$$\mathrm{Re}\,al \sum_{n=1}^{6} (C_4 \exp(\beta_4 X) + C_5 \exp(\beta_5 X + C_6 \exp(\beta_6 X) + y_2 \exp(-\mu X) \exp(in\omega t)$$

The arbitrary constants C1, C2, C3, C4,C5, C6 can be determined from the following set of boundary conditions:

$$-K_m dT_m(d,t)/dX = h_f(T_f(d,t)-T_a(t)) \quad (12)$$

$$\dot{m}C_{pf}(T_{co}(t)-T_f(0,t)) = h_f(T_{co}(t)-T_m(0,t)) \quad (13)$$

$$-K_m dT_m(0,t)/dX = h_f(T_f(0,t)-T_m(0,t)) \quad (14)$$

Application of boundary conditions in eqs. (9-10) yield the following, 3 X 3 matrixes for time independent part & time dependent parts. The porous absorber temperature & fluid temperature can be obtained by substituting x=d in equ. (10) andsubstituting equ. (10) inequ. (2) repectively.

Table 1a: Dimensions and Physical Properties of the Plastic Air Heaters

S. No	Components of systems/Collector type	Collector-I Non-porous	Collector-II non-porous	Collector-III porous	Collector IV porous	Collector V porous	CollectorVI porous	CollectorVII porous	CollectorVIII porous
1	Length of collector	9.10	9.15	8.85	8.80	17.6	9.20	9.6	9.5
2	Width of collector	1.10	0.92	1.03	1.15	1.13	0.89	0.85	0.94
3	Absorbing area (m2)	10.0	9.02	9.12	10.12	19.89	9.02		
4	Cross sectional area of the collector at the inlet and outlet (m2)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
5	Material of cover	PVC	PVC	PVC	PVC	PVC	PVC	PVC	PVC
6	Thickness of cover(mm)	0.6	0.15	0.6	0.6	0.6	0.60	0.60	0.60
7.	Transmittance of PVC Cover	0.829	0.94	0.83	0.83	0.83	0.83	0.83	0.83
8	Thickness of inside PVC Cover (mm)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

4.0 Results and Discussion

The results of the experiments conducted for several low cost plastic collectors used for low temperature applications are shown in table-(2) respectively.

The specifications of various plastic collectors used for air & water are shown in table-1(a) to 1(b) respectively. The performance of nonporous and porous collectors for different mass flow rates are shown in Fig-1

Table 1b: Performance and Physical Parameters and Dimensions of Other Solar Hot Water Systems

S. No	Dimensions/ physical parameters Of different plastic water heaters Used for low temperature applicat-Ions in rural areas.	Shallow solar pond water heater using PVC collector	Shallow solar pond water heater using polyvinyl Fluoride collector	Conventional water heating system
1	Length of the collector surface	2.05 m	2.05 m	2.05 m
2	Breadth of the collector surface	1.0 m	0.94 m	0.84 m
3	Storage capacity	100Litres	100Litres	100Litres
4	Glazing	Double cover of PVC	Double cover of fluoro-polymer	Double glass of 4 mm thick
5	Absorber	PVC of 0.6mm	0.1 mm thick PVF	Copper plate
6	Collector inclination to the horizontal surface	Zero Deg.	Zero Deg	40 Deg.

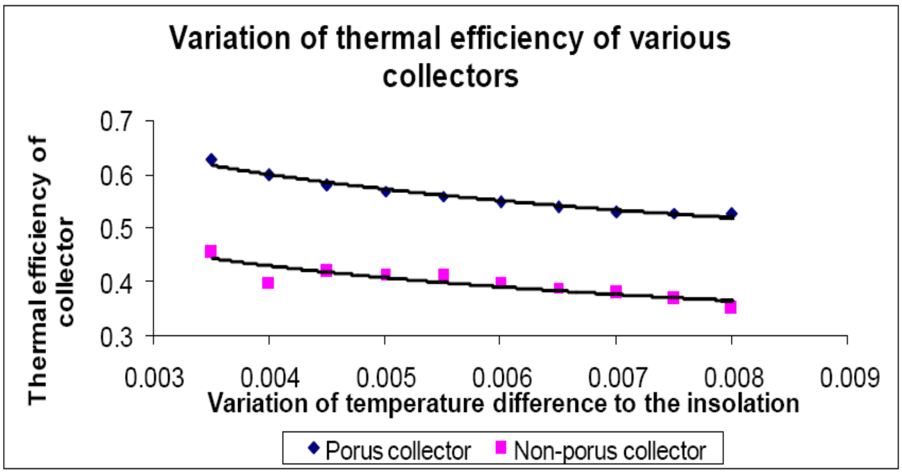

Table 2: Performance of Low Cost Plastic Porous and Non Porous Collectors Used for Low Temperature Applications

S. No	Mass flow Rate (m^3/hr)	Temperature rise (^oC)	Temperature rise (^oC)	Temperature rise (^oC)
1	420	23.4 (900 W/m^2)	23.9 (748W/m^2)	22.8 (732 W/m^2)
2	545	19.4 (836 W/m^2)	18.0 (682 W/m^2)	20.4 (746 W/m^2)
3	645	18.2 (876W/m^2)	18.4 (800 W/m^2)	19.2 (743 W/m^2)
4	718	17.4 (908 W/m^2)	13.9 (656 W/m^2)	18.8 (752 W/m^2)
5	770	15.9 (855 W/m^2)	13.9 (700 W/m^2)	18.3 (759 W/m^2)
6	Insulation type	3 cm thick polyethylene	3 cm thick polyethylene with Al. foil above it	6 cm thick polyethylene

Table 3: Performance of Porous Absorber Plastic Collector S with Different Back Insulation

Type of insulation	Mass flow rate (m3/hr)	3 cm thick polyethylene	3 cm thick polyethylene with Al. foil above it.	6 cm thick polyethylene
S.No	Efficiency	Efficiency (%)	Efficiency (%)	Efficiency (%)
1	420	39.991	49.05	47.81
2	545	46.22	52.57	54.47
3	645	48.98	54.27	60.90
4	718	50.29	55.60	65.67
5	770	52.33	55.88	67.85

Table 4: Performance of Low Cost Plastic Porous Collector Used for Low Temperatures

S. No	Ambient air temp. (oC)	Solar intensity (W/m2)	Mass flow rate of air (m3/hr)	Inlet temp of air (oC)	Outlet temp of air (oC)	Temp Diff (oC).	Qu Watt (Theort.	Qu Watt. Exp.	Eff. %
1	20.3	900	730	20.1	29.9	9.8	2383	2020	26.5
2	20.4	900	700	21.7	31.8	10.1	2356	2030	26.2
3	20.8	900	660	21.6	33.1	10.5	2310	2011	25.7
4	21.2	900	610	21.6	32.6	11.0	2237	1992	24.8
5	21.8	900	520	21.7	33.3	11.6	2009	1789	22.3
6	21.7	900	410	21.7	33.9	12.2	1665	1501	18.5
7	20.1	900	270	29.1	39.8	17.9	1602	1490	17.8

Table 5: Thermal Performance of Low Cost Plastic Porous Collector

S.No	Ambient air temp. (oC)	Solar intensity (W/m2)	Mass flow rate of air (m3/hr)	Inlet temp of air (oC)	Outlet temp of air (oC)	Temp Diff (oC).	Qu Watt (Theort.)	Qu Watt.E xp.	Eff. %
1	20.3	900	730	20.3	36.6	16.3	3966	3603	48.3
2	20.4	900	700	20.4	37.3	16. 9	3942	2616	48.0
3	20.8	900	660	20.8	38.2	17.4	3826	3527	46.6
4	21.2	900	610	21.2	39.4	18. 2	3698	3453	45.1
5	21.8	900	520	21.8	41.2	19.4	3557	3137	40.9
6	21.7	900	410	21.7	45.9	24.2	3195	3031	38.9
7	20.1	900	270	20.1	50.6	30.5	2742	2630	33.4

Table 6: Thermal Performance of Low Cost Plastic Porous Collector

S.No	Ambient air temp. (oC)	Solar intensity (W/m^2)	Mass flow rate of air (m^3/hr)	Inlet temp of air (^{o}C)	Outlet temp of air (^{o}C)	Temp Diff (^{o}C).	Qu Watt (Theort.)	Qu Watt.Exp.	Eff. %
1	20.3	900	730	20.3	36.6	16.3	3966	3603	48.3
2	20.4	900	700	20.4	37.3	16. 9	3942	2616	48.0
3	20.8	900	660	20.8	38.2	17.4	3826	3527	46.6
4	21.2	900	610	21.2	39.4	18. 2	3698	3453	45.1
5	21.8	900	520	21.8	41.2	19.4	3557	3137	40.9
6	21.7	900	410	21.7	45.9	24.2	3195	3031	38.9
7	20.1	900	270	20.1	50.6	30.5	2742	2630	33.4

Table 7: Thermal performance of Four Low Cost Plastic Collectors Cum Storage Systems Used for Drying Applications in the Rural Areas

Time (hour)	Ambient temp(oC)	Insolation (W/m2)	Collection Eff. (%) Ist collector	Collection Eff.(%) II collector	Collection Eff.(%) III collector	Collection Eff.(%) IV collector
8 A.M.	28.5	250.0	0.0	0.0	0.0	0.0
9.0	30.0	425.0	40.97	45.52	43.59	48.4345
10.0	31.0	600.0	54.23	44.53	57.69	47.38
11.0	32.0	725.0	34.15	37.94	36.326	40.36
12.0	33.0	825.0	31.79	29.97	33.8	31.886
13.0	34.0	830.0	15.15	22.72	16.512	24.17
14.0	35.0	795.0	19.32	20.49	16.412	21.796
15.0	35.5	625.0	8.0	16.93	20.56	18.013
16.0	35.0	450.0	0.0	15.52	8.72	16.51
17.0	34.0	250.0	0.0	0.0	0.0	0.0
18.0	32.0	50.0	0.0	0.0	0.0	0.0

Table 8: Thermal Performance of Low Cost Plastic Porous Collector for Crop Drying Applications in Rural Remote Areas

S. No	Ambient air temp. (oC)	Solar intensity (W/m2)	Mass flow rate of air (m3/hr)	Inlet temp of air (oC)	Outlet temp of air (oC)	Temp Diff (oC).	Qu Watt (Theort.)	Qu Watt. Exp.	Eff. %
1	20.2	900	730	20.2	37.0	16.8	4086	3723	22.7
2	19.9	900	700	19.9	37.4	17.5	4082	3756	22.6
3	18.7	900	660	18.7	36.9	18.2	4001	3702	22.2
4	19.5	900	610	19.5	38.2	18. 7	3796	33553	21.1
5	18.7	900	520	18.7	338.8	20.1	3481	3261	19.3
6	20.0	900	410	20.0	40.6	20.6	2813	2649	15.6
7	21.9	900	270	21.9	48.0	26.1	2345	2233	13.0

The performance of systems for 90 liters daily hot water demand have been computed and it was observed that low cost plastic air and water heating collectors can replace conventional air and water heating systems in the rural & remote areas. From techno-economic optimization of these systems indicate that inserting auxiliary electric heater inside hot water storage tank connected with collectors is not economically feasible than provision of auxiliary electric heater at the load point during cloudy days because it has 20% more heat losses in the hot water storage tank. The costs of these systems (by considering life time of conventional systems of 18 years along with six years of plastic collectors) have been compared for same capacity. It was observed that cost of water heating systems using plastic collectors is less than 25% than conventional hot water systems.

Table 9: Thermal Performance of Four Low Cost Plastic Collectors Cum Storage Systems Used for Drying Applications in the Rural Areas

Time (hour)	Ambient temp(oC)	Insolation (W/m2)	Collection Eff. (%) Ist collector	Collection Eff.(%) II collector	Collection Eff.(%) III collector	Collection Eff.(%) IV collector
8 A.M.	28.5	250.0	0.0	0.0	0.0	0.0
9.0	30.0	425.0	40.97	45.52	43.59	48.4345
10.0	31.0	600.0	54.23	44.53	57.69	47.38
11.0	32.0	725.0	34.15	37.94	36.326	40.36
12.0	33.0	825.0	31.79	29.97	33.8	31.886
13.0	34.0	830.0	15.15	22.72	16.512	24.17
14.0	35.0	795.0	19.32	20.49	16.412	21.796
15.0	35.5	625.0	8.0	16.93	20.56	18.013
16.0	35.0	450.0	0.0	15.52	8.72	16.51
17.0	34.0	250.0	0.0	0.0	0.0	0.0
18.0	32.0	50.0	0.0	0.0	0.0	0.0

Table 10: Thermal Performance of Low Cost Plastic Collector Cum Storage System Using Air/Water Heat Exchanger (for Mass of Water =90Kg.)

Time (hour)	Ambient temperature oC)	Insolation (W/m2)	Hot water temperature (oC)	Useful Energy (W)	Collection Efficiency (%)
8 A.M.	28.5	250.0	28.5	0.0	0.0
9.0	30.0	425.0	30.5	210.0	40.97
10.0	31.0	600.0	35.0	472.5	54.23
11.0	32.0	725.0	39.0	420.0	34.15
12.0	33.0	825.0	43.5	472.5	31.79
13.0	34.0	830.0	46.0	262.5	15.15
14.0	35.0	795.0	48.5	315.0	19.32
15.0	35.5	625.0	51.5	105.0	8.0
16.0	35.0	450.0	52.5	0.0	0.0
17.0	34.0	250.0	52.0	0.0	0.0
18.0	32.0	50.0	51.5	0.0	0.0

Table 11: Thermal Performance of Low Cost Plastic Collector Cum Storage System for Second Day .(for Mass of Water =90Kg.)

Time	Ambient temperature oC)	Insolation (W/m2)	Hot water temperature (oC)	Useful Energy (W/m2)	Collection Efficiency (%)
8 A.M.	25.5	22.5	25.5	0.0	0.0
9.0	27.0	450.0	29.0	367.5	45.52
10.0	28.5	575	33.0	420.0	44.53
11.0	31.5	675.0	38.0	525.0	37.94
12.0	32.5	769.0	43.0	472.5	2997
13.0	34.5	789.0	47.5	367.5	22.72
14.0	35.5	750.0	51.0	315.0	20.49
15.0	36.0	605.0	54.0	210.0	16.93
16.0	35.0	495.0	56.0	157.5	15.52
17.0	34.0	235.0	57.5	0.0	0.0
18.0	32.0	65.0	57.0	0.0	0.0

References

[1] Schuman, “Heat transfer in liquid flowing through porous prism” Fannkin Institute, 1929, 204, pp-405

[2] Dunckle, “Randomly packed particle bed regenerator and evaporative coolers” Trans. Institute of Engineering (Australia), 1972, pp-117-120

[3] G. O. G. Lof, “Unsteady state heat transfer between air and loose solids” Journal of Industrial Engg Chemistry, 1948, 40, pp-1061-64

[4] N. K. Bansal, R. S. Mishra, ” Effect of Boundary conditions on the matrix air heaters” International Journal of Energy Conversion & Management, 1984, pp-291-294

[5] R. S. Mishra, “Design, Development and techno-economic evaluation of hybrid solar air heating cum storage systems for space heating and crop drying”, Proc. Eigth national conf. of mechanical engineers, University of Roorkee, 1992, pp-24-32

[6] R. S. Mishra “Evaluation of thermal performance of ventilating Trombe wall for porous and non porous structures” Ninth National conference on mechanical engineering, IIT Kanpur-pp-175-181.

[7] R. S. Mishra, “Thermal performance of thermal energy storage rock bed systems system for space heating and crop drying”, International conference on advances in mechanical and industrial engineering, University of Roorkee, 1997, pp-553-565

[8] R. S. Mishra, “Thermal performance of low cost rock bed thermal energy storage system for space heating and crop drying” International conference on research and development, Vision-21st century, 1999, pp-235-243