SASEC2015
Third Southern African Solar Energy Conference
11 – 13 May 2015
Kruger National Park, South Africa

SOLAR ALUMINIUM TUBULAR AIR HEATER

Rane M V*,[a], Joshi S M[b] and Bhave D P[a]
*Author for correspondence
[a]Heat Pump Laboratory, Department of Mechanical Engineering,
Indian Institute of Technology Bombay, Powai
Mumbai, 400 076,
INDIA,
E-mail: ranemv@iitb.ac.in, dakshata.bhave@gmail.com
[b]Department of Mechanical Engineering
MES's PIIT EMSR, New Panvel
Navi Mumbai, 410 206,
INDIA
E-mail: smjoshi@mes.ac.in

ABSTRACT

Efficient, cost effective and light weight solar collectors to meet the low temperature needs, at or below 100°C will be the better option for utilisation of solar energy in developing countries like India. Test results of a patented low cost light weight modular solar collector developed and tested at Heat Pump Laboratory at IIT Bombay, HPL_IITB, (19°07′ N 72°51′ E) are presented. A 5 m^2 aperture collector was installed on HPL_IITB terrace with an optimum tilt of 47° for the month of December. Heat delivered by the collector in terms of ambient air heated to 70.3°C, at average mass flow rate of 53.9 g/s, over 9 h test period was 21.5 kWh with an efficiency of 70.2%. Power consumed by air circulating fan was less than 1% of the heat delivered by the collector. Weight of this novel collector is only 7.6 kg/m^2. Collector costs approximately INR 5,000/m^2 (USD 82/m^2) which works out to be about INR 1,200/kWh.d^{-1} (USD 20/kWh.d^{-1}). Payback calculated, without any subsidy, when used for industrial heating applications is approximately 252 days.

INTRODUCTION

A large part of industrial, commercial and residential energy need consists of heating at low temperatures, at or below 100°C. Some of the applications are drying, space heating, washing, pasteurizing, bleaching, dying and pickling. Fossil fuels or electricity have also been traditionally used for these applications. It is desirable to reduce use of fossil fuels for this purpose due to their short supply and price fluctuations and concerns of pollution associated with exhaust emissions. Solar energy can be a good clean alternate source of energy for above applications.

Large scale use of solar energy for various applications has not been possible because it is usually not found to be cost effective and high parasitic power requirement. High cost and weight, maintenance including need for adjustment of tracking mechanism and need for suitable installation space are some of the main deterrents for wide spread use of solar energy. Novel Patented solar collectors developed at HPL_IITB address above issues in an innovative way. One of these solar collectors, Solar Aluminium Tubular Air Heater, SATAH, which promise good techno-economic viability, is described in this paper. Test results of this collector for a typical day are presented and payback period is estimated for industrial heating needs.

NOMENCLATURE

dp	[Pa]	Pressure drop
dt	[°c]	Temperature difference
E	[W/m^2]	Solar Insolation
IST	[h]	Indian Standard Time
mf	[g/s]	Mass flow rate
pb	[W]	Blower power
Q	[W/m^2]	Heat duty
T	[°C]	Temperature

Special characters

η	[%]	Efficiency

Subscripts

a	Air
i	Incoming, inlet
o	Outlet
sc	Solar collector
tot	Total

SOLAR ALUMINIUM TUBULAR AIR HEATER, SATAH

A conventional flat plate solar air heater essentially consists of an absorber plate, a transparent cover on the top, and insulation on the bottom and sides. The assembly is encased in sheet metal. Literature review related to flat plate solar air heaters reveals following technological gaps:

a. Single top cover made of glass is unable to reduce the top loss significantly, resulting in low efficiency
b. Multiple top covers reduces top losses, but results in increased weight and cost
c. Conventional 2 m^2 panels are unable to increase the temperature of air through 45 to 50^oC in one pass; several panels need to be connected in series, which results in larger pressure drops and increased blower power.

These gaps have to be addressed for cost effective and large scale deployment of flat plate solar collectors. There has been a longstanding need to provide a flat plate solar air heater featuring reduced top loss while keeping the weight of the collector low; enhancing efficiency while reducing the pressure drop and power required for circulation and keeping the cost low while being capable of meeting space air heating needs in ambient as low as -30^oC. Use of low cost light weight plastic materials have been reported by Njomo (1995), Janjai et al. (2000), Rane (2004), Popel et al. (2008), Rane and Joshi (2011).

A novel solar air heater, Solar Aluminium Tubular Air Heater SATAH, is developed and patented (Rane, 2004 and Rane *et al.* 2014) by the Heat Pump Laboratory at IIT Bombay, HPL_IITB, which addresses many of the technical gaps of commercially available flat plate solar air heaters and opens up possibilities for use in various applications. This solar air heater comprises of a transparent multi-wall polycarbonate top cover, blackened thin wall aluminium tube absorber, inlet manifold to take ambient air in, central hot air collection header, blower for circulation of air which can be operated on solar power and rigid closed cell foam insulation panels, lined with aluminium foil, as durable back cover.

Assuming 5 to 6 kWh/m^2.d solar insolation on horizontal surface and about 60% efficiency of the collector, the hot air at about 40 to 90^oC can be delivered serving applications like space heating, industrial hot air or agro products drying. A temperature rise of about 60^oC is expected even at -30^oC ambient. Lifespan of these air heaters is expected to be 10 to 15 year and can be extended beyond 20 year by replacing some components.

This light weight non-tracking flat plate collector can be mounted on existing roof or integrated as a roof for new construction. Some of the features of this Solar Tubular Air Heater, SATAH are listed as below

a. Modular, light weight and easy to transport
b. Free from moving parts other than a fan. Low pressure drop enables use of PV operated fan to make the system grid independent
c. Use of glass is avoided and metal is minimized

Design philosophy, fabrication details and experimental results of subsequently developed, fabricated and tested 5 m^2 aperture area SATAH are presented here. Collector is designed by assuming solar insolation of 1000 W/m^2 on collector plane. A 10 mm multiwall clear polycarbonate sheet with solar transmittance of 0.85 is used as top cover. Maintaining laminar flow of air inside the absorber tube helps decoupling pressure drop and heat transfer rate and reduces fan power required. Heat transfer coefficient inside the absorber tube calculated for laminar flow was 16.7 W/m^2K. Higher heat transfer coefficient in turn maintains comparatively low temperature driving force between inside wall of absorber tube and air flowing through the collector. This results in reduced temperature of absorber wall and in turn reduced re-radiation and convection heat loss from the absorber tube surface as well as convective top loss, Figure 1. An insulation panel with thermal conductivity 0.021 W/m.K and 40 mm thick has restricted the bottom loss to 1.32 W/m^2. Side losses are very negligible as the inlet manifold for atmospheric air is incorporated in longer side frame. Heat absorbed as well as incident on side frame is utilised for preheating incoming air which helps keeping the frame temperature near to atmosphere resulting in reduced side loss.

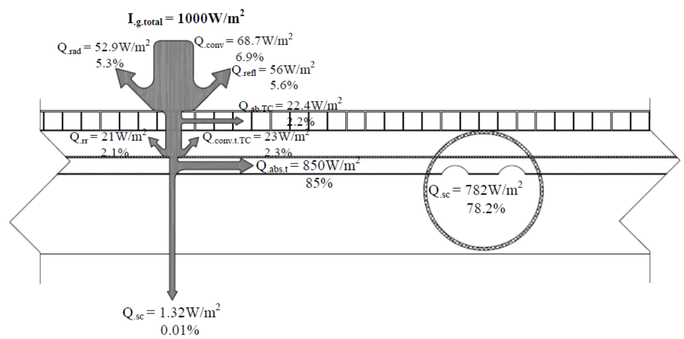

Figure 1 Heat Trace Diagram for SATAH

The first prototype of SATAH was installed on HPL_IITB terrace with a tilt of 19^o Figure 2 and Figure 3.

Tilt helps avoid very high stagnation temperatures by enabling natural convection of ambient air through the collector when blowers are not operated during sunshine hours.

During preliminary tests the ambient air was heated up to 119.5^oC at an insolation of 879 W/m^2. The pressure drop in the collector was 30 Pa, however hot air flow was limited to 8.4 g/s or 1.6 g/s.m^2 using a 6.5 W 24 VDC Orix MBD8-24 blower.

Hot air drawn through the collector was cooled in a water cooled heat exchanger before being drawn using the DC blower which could handle hot air at a maximum of 60^oC. Though the pressure drop through the collector was low, pressure drop across the air cooler has increased the total head required across the blower to about 180 Pa. Collector efficiency achieved was only 37% as air temperature was high due to limited air flow.

To increase the air flow rate two 92 W nominal rated power, ebm-papst 230VAC RLH120/3800-3038 LH, hot air blowers were deployed to directly draw hot air through the collector. This has increased the efficiency of the SATAH.

Tests data for 27/09/2013, a typical test day, Figure 4 and Figure 5, indicates that the ambient air could be heated up to 85.7^oC with an instantaneous efficiency 48.9% at an insolation of 891W/m^2. Ambient air temperature for 6 and 9 h average was 27.9 and 26.9^oC. Hot air temperature coming out from the collector was 76.1 and 64.8^oC respectively. Average solar insolation for 6 and 9 h period was 756 and 609 W/m^2 and the air flow rate was 39.8 and 41.5 g/s (7.9 and 8.3 g/s.m^2) respectively. Average efficiency recorded was 50.8 and 48.3% respectively for 6 and 9 h test period.

Figure 2 Photograph of SATAH Test Set Up

At peak solar insolation the temperature difference across the collector was 55.5^{o}C and collector efficiency achieved was increased to 48.9% from earlier 37%, but was not as high as expected as the air flow was lower than the design value of 44.2 g/s or 8.9 g/s.m^{2}for an isolation of 891 W/m^2. Actual air flow rate was 23.6% lower than this value.

The pressure drop across the collector was 165 Pa. Instantaneous total power consumed by both the fans was 158 W or 0.95 kWh and 1.4 kWh for 6 and 9 h operation respectively.

To reduce the air side pressure drop header configuration was altered by providing multiple outlets. Use of three outlets in SATAH-V1 reduced the pressure drop across the collector to 50 Pa. This in turn reduced the pumping power to 31.9 W. Details are explained in forthcoming sections of the paper.

This collector was installed with an optimum tilt for the month, this helps tapping maximum solar energy and resulting in enhanced thermal performance.

Time	Collector Parameters					Blower Power			Air Flow Rate			Collector Performance			
IST	$E_{t.sc}$ W/m^2	$t_{a.i}$ ^{o}C	$t_{a.o}$ ^{o}C	dt_{sc} ^{o}C	dp_{sc} mm H_2O	$V_{b.DC}$ V	I_b A	P_b W	$va_{b.o.av}$ m/s	$mf_{a.sc}$ g/s	$mf_{a.sc}$ g/s.m^2	$Q_{i.tot}$ kW	$Q_{sc.tot}$ kW	η_{sc} %	$Q_{sc.m^2.ab}$ kW/m^2
8:30	439	20.9	38.2	17.3	16.5	192	0.4	157	6.9	44.5	8.9	2.2	0.8	35.6	0.16
9:30	557	23.3	53.7	30.4	16.5	193	0.4	158	6.9	42.4	8.5	2.8	1.3	47.0	0.26
10:30	735	25.6	71.4	45.8	16.5	194	0.4	159	6.9	40.2	8.0	3.6	1.9	50.9	0.37
11:30	840	27.6	81.6	54.0	16.5	193	0.4	158	6.9	39.1	7.8	4.2	2.1	51.0	0.43
12:00	878	28.9	83.6	54.7	16.5	193	0.4	158	6.9	38.9	7.8	4.3	2.1	49.2	0.43
12:30	891	30.2	85.7	55.5	16.5	193	0.4	158	6.9	38.6	7.7	4.4	2.2	48.9	0.44
13:00	831	30.7	84.9	54.2	16.5	193	0.4	158	6.9	38.7	7.7	4.1	2.1	51.3	0.43
13:30	816	30.3	83.4	53.1	16.5	193	0.4	158	6.9	38.9	7.8	4.0	2.1	51.4	0.42
14:30	700	28.5	73.2	44.7	16.5	193	0.4	158	6.9	40.0	8.0	3.5	1.8	51.9	0.36
15:30	537	27.4	60.4	33.0	16.5	192	0.4	157	6.9	41.6	8.3	2.7	1.4	51.9	0.28
16:30	326	27.3	39.0	11.7	16.5	193	0.4	158	6.9	44.4	8.9	1.6	0.5	32.4	0.11
17:30	65	24.9	24.7	-0.2	16.5	194	0.4	159	6.9	46.6	9.3	0.3	0.0	-2.9	0.00
Avg 6h	756	27.9	76.1	47.8	16.5	193	0.4	158	6.9	39.8	7.9	3.6	1.9	50.8	0.37
Avg 9h	609	26.9	64.8	38.1	16.5	193	0.4	158	6.9	41.5	8.3	3.1	1.5	48.3	0.30
Avg 6h		$Q_{.sc.tot}$	2.25	kWh/m^2			Cost	2293	INR/kWh.m^2.d			Weight		7.6	kg/m^2
Avg 9h			2.69	kWh/m^2				1916	INR/kWh.m^2.d						

Figure 4 SATAH Test Data, Date of Experiment 27/09/2013

Two identical, high temperature, PV operated DC fans were deployed to modulate air flow rate in response to solar insolation.

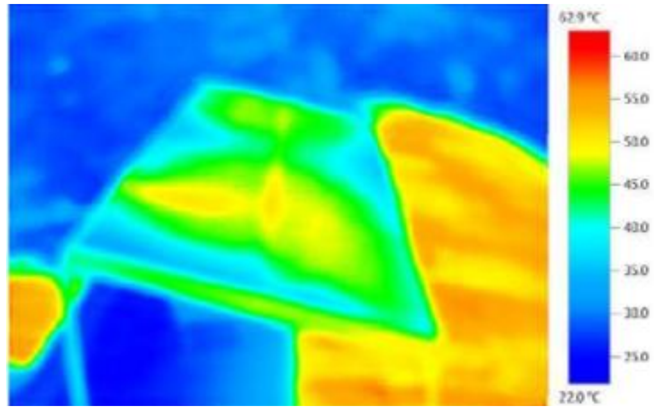

Figure 3 Thermal Image of SATAH Test Set Up

FABRICATION OF SATAH-V1

A SATAH-V1 of size 4.1 m L x 1.22 m W, with double UV stabilized 10 mm twin wall clear polycarbonate top cover was fabricated. Absorber is made of 227 blackened aluminium tubes of 9 mm OD x 0.6 mm thick to heat ambient air. All these tubes were connected to central hot air collection header. Aluminium pipe of 60 mm OD x 1.5 mm thick was used as hot air collection header which rests on 40 mm thick both side aluminised PIR insulation panel. Absorber tubes were secured in an inlet manifold along both the ends and passed through and through the hot air collection header to deliver hot air in the header. Aluminium extrusion of size 76.2 mm was used as frame to hold the top cover, inlet manifold along with absorber tubes and insulation sheet together as well as to strengthen the collector assembly.

This light weight predominantly plastic flat plate solar tubular air heater weighs only 7.6 kg/m^2. This has been achieved by using multiwall polycarbonate sheet as top cover, use of thin and light weight aluminium tubes as absorber surface, eliminating air inlet headers and using rigid closed cell foam insulation panels lined with aluminium foil as durable back cover.

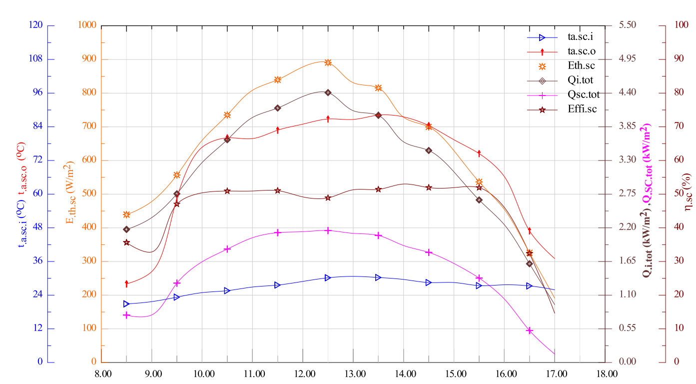

Figure 5 Results of Experiment on SATAH, dated 27/09/2013

To increase the air flow rate, a 24 VDC and 40 W nominal rated power, ebm-papst DV6224, hot air diagonal compact fan was deployed to directly draw hot air through the collector.

INSTALLATION AND TESTING OF SATAH-V1

SATAH-V1 was installed on old terrace of HPL_IITB with an optimum tilt of 47^o for the month of December. Photograph of experimental set up and the thermal image of SATAH-V1 is shown in Figure 6 and Figure 7 respectively.

Test data such as ambient air temperature at collector inlet and hot air temperature at collector outlet, pressure drop across the collector was continuously acquired with an interval of one minute through NI data acquisition system. This data was averaged out over half an hour for calculations. Solar insolation was measured on SATAH plane by Suryamapi. Hot air from collector outlet was discharged in the duct placed underneath the collector. High temperature fan was installed at another end of the duct. Air velocity was measured at nine different locations along the periphery of 165 mm diameter fan by testo 410-2 vane type anemometer and then averaged out for the calculations.

It is seen in the thermal image that major portion of the top cover is at about 41 to 45^{o}C temperature. The high temperature is due to central hot air collection header, whereas along the sides the temperature is near to atmospheric temperature as the air inlet to the collector is along the long sides of the unit.

RESULTS AND DISCUSSION

Typical data for one of the tests conducted on 6/12/2014 for a period of 9 h from 830 hrs to 1730 hrs is presented in Figure 8. Average solar radiation on collector plane was 891 and 687 W/m^2 for 6 and 9 h period respectively.

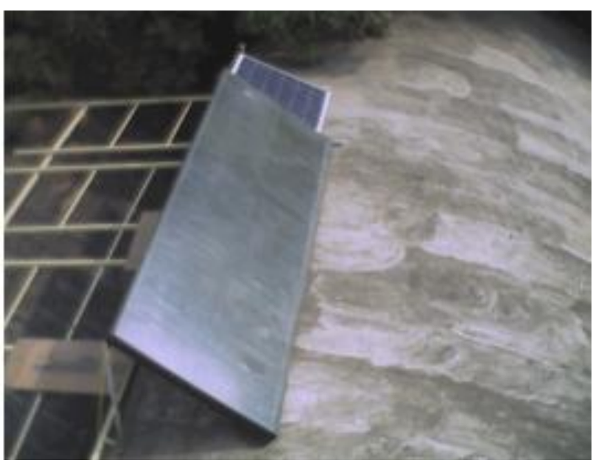

Figure 6 Photograph of SATAH-V1 Test Set Up Installed on HPL_IITB Terrace

Ambient air temperature averaged over 6 and 9 h respectively was 33.3 and 32.5^{o}C, it was heated up to 82.6 and 70.3^{o}C respectively for 6 and 9 h period Total average heat duty delivered by the collector was 19.9 and 21.5 kWh with an average efficiencies of 75.3 and 70.2%. Mass flow rate of air was modulated with respect to solar radiation as fan used for circulating air was run through DC power from a PV panel. Thus the average mass flow rate of air was 66.7 and 53.9 g/s or 13.3 and 10.8 g/s.m^2 respectively during the test period. Pressure drop across the collector was measured as 4.6 to 5 mm of water column i.e. 46 to 50 Pa. Average power consumed by fan was ranging from 24.8 to 31.9 W. Collector cost was estimated about 5,000 INR/m^2 thus referring to heat duty of the collector, cost of the collector derived as INR 1,420 kWh/d or approximately USD 22.8 kWh/d based on 6 h working it further comes down to INR 1,200 kWh/d or USD 19.2 kWh/d for 9 h utilisation.

Peak solar radiation was observed from 1200 to 1300 hrs on the test day. Instantaneous highest temperature of hot air is recorded as 89.9^{o}C at insolation of 1090 W/m^2 on collector plane. Highest average temperature for a period of half an hour was 88.2^{o}C between 1300 to 1330 hrs. Average solar insolation recorded was 983 W/m^2 on collector plane. Ambient air temperature then was 35^{o}C. Apparently highest temperature was observed at comparatively lower solar intensity. This may be due to intermittent cloudy sky in this period. Sudden drop in intensity of solar radiation was observed from 1530 hrs and thereafter, this is due to winter season and shorter day lengths in the month of December in India.

Installed solar PV panel was under partial shading till 900 hrs. Due to which even at 452 W/m^2 solar insolation, average power generated and supplied to fan was as low as 5 W this led to lesser mass flow rate of air i.e. 14.6 g/s as against average 42.8 g/s at 464 W/m^2 in the next half an hour, during 900 to 9.30 hrs.

Figure 9 representing results of the test conducted on 6/12/2014.

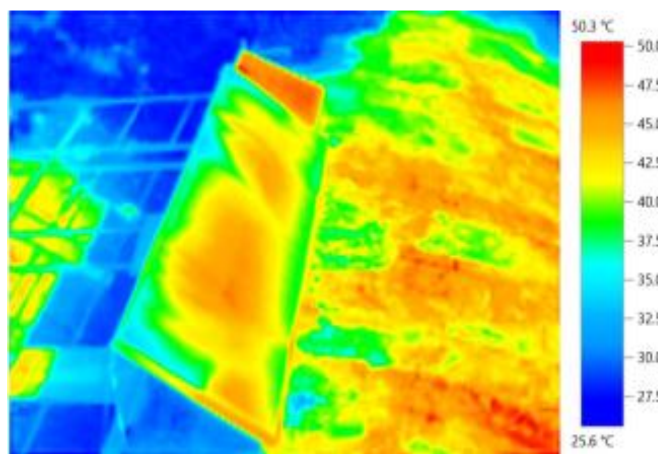

Figure 7 Thermal Image of SATAH_V1 Test Set Up

Also the efficiency from 1000 hrs to 1600 hrs is above 63%. This is due to mass flow rate of air flowing through SATAH automatically tuned to solar insolation available as the fan is running on DC power input from PV panel.

Next generation SATAH have also been developed and tested in which the pressure drop across the collector is further reduced to 16 Pa. The performance testing of next generation SATAH is in progress and preliminary results are very encouraging. Six panels of 3 m^2 each are being tested at potential licenser's sites for use in industrial applications and also for tea drying application.

Time	Collector Parameters						Air Flow Rate			Collector Performance			
IST	$E_{t.sc}$ W/m^2	$t_{a.i}$ ^oC	$t_{a.o}$ ^oC	dt_{sc} ^oC	dp_{sc} mm H_2O	P_b W	$va_{b.o.av}$ m/s	$mf_{a.sc}$ g/s	$mf_{a.sc}$ $g/s.m^2$	$Q_{i.tot}$ kW	$Q_{sc.tot}$ kW	η_{sc} %	$Q_{sc.m^2.ab}$ kW/m^2
08:30	***452***	*24*	*28.0*	*4.1*	*3.2*	*5.0*	*1.0*	*14.6*	*2.9*	***2.2***	***0.06***	**2.7**	***0.01***
09:30	***464***	*25*	*58.6*	*33.2*	*4.3*	*12.5*	*3.1*	*42.8*	*8.6*	***2.3***	***1.43***	**62.0**	***0.29***
10:30	***751***	*29*	*80.0*	*50.9*	*5.1*	*21.3*	*4.2*	*54.1*	*10.8*	***3.7***	***2.77***	**74.5**	***0.56***
11:30	***992***	*32*	*82.8*	*50.5*	*4.9*	*30.4*	*5.9*	*75.9*	*15.2*	***4.9***	***3.85***	**78.5**	***0.78***
12:00	***1089***	***33***	***84.9***	***52.0***	***5.1***	***37.4***	***6.3***	***80.1***	***16.0***	***5.4***	***4.19***	**77.8**	***0.85***
12:30	***1030***	***34***	***86.8***	***52.9***	***5.2***	***38.0***	***5.9***	***74.9***	***15.0***	***5.1***	***3.99***	**78.2**	***0.81***
13:00	***1030***	***35***	***86.6***	***52.0***	***5.2***	***39.1***	***5.9***	***75.4***	***15.1***	***5.1***	***3.94***	**77.3**	***0.80***
13:30	***983***	*35*	*88.2*	***52.9***	*5.2*	*38.9*	*5.5*	*69.6*	*13.9*	***4.9***	***3.70***	**76.1**	***0.75***
14:30	***874***	*36*	*84.4*	***48.4***	*5.0*	*31.7*	*5.0*	*63.4*	*12.7*	***4.3***	***3.08***	**71.3**	***0.62***
15:30	***607***	*36*	*74.5*	***38.3***	*4.5*	*29.0*	*4.4*	*57.5*	*11.5*	***3.0***	***2.21***	**73.7**	***0.45***
16:30	***221***	*35*	*46.9*	***12.4***	*4.1*	*13.7*	*2.3*	*33.1*	*6.6*	***1.1***	***0.41***	**37.7**	***0.08***
17:30	***98***	*31*	*32.7*	***1.5***	*3.3*	*3.7*	*1.2*	*17.2*	*3.4*	***0.5***	***0.03***	**5.5**	***0.01***
Avg 6h	***891***	***33.3***	***82.6***	***49.3***	***5.0***	***31.9***	***5.2***	***66.7***	***13.3***	***4.4***	***3.3***	***75.3***	***0.67***
Avg 9h	***687***	***32.5***	***70.3***	***37.8***	***4.6***	***24.8***	***4.1***	***53.9***	***10.8***	***3.4***	***2.4***	***70.2***	***0.48***
Avg 6h			***$Q_{.sc.tot}$***	***4.03***	***kWh***	***1241***		***INR/kWh.m^2.d***			***Weight***	***7.6***	**kg/m^2**
Avg 9h				***4.34***	***kWh***	***1151***		***INR/kWh.m^2.d***					

Figure 8 Test Data for SATAH, Date of experiment 6/12/2014

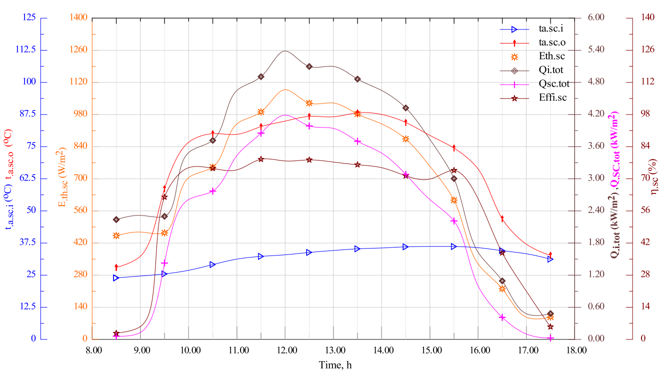

Figure 9 Results of Experiment on SATAH dated 6/12/2014

Features of this Solar Aluminium Tubular Air Heater are as follows

a. Multiwall polycarbonate top cover offers advantages of double glazed collector at significantly reduced cost and weight. Reduced top loss results in improved efficiency
b. Due to small diameter of absorber tube and operating in laminar flow regime air side heat transfer coefficient is increased up to 18 W/m^2K which results in reduced temperature of absorber surface. Lower temperature of absorber surface for a given application reduces radiation and convection losses from the absorber surface which leads to increased collector efficiency.
c. Higher heat transfer coefficient help achieving high temperatures in shorter absorber length. Ambient air heating up to 86.8°C is achieved in o.6 m long flow passage in once through mode.
d. Inlet manifold is a part of frame of this collector. Frame is blackened and hence absorbs beam as well as diffused solar radiation. This absorbed energy preheats ambient air entering into the inlet manifold and thus maintains frame temperature near to ambient to reduce side losses. Preheating helps increase in air temperature at collector outlet or increased volume flow rate which in turn leads to increase in efficiency.
e. Increased efficiency leads to reduction in size of the collector which results in reduced initial investment and realizes early payback.
f. Ease in integration of all the components as anp assembly of a solar heater which can be installed on existing roof tops or may be used as roof top for new construction.
g. Modular design offers freedom of need based utility
h. PV operated fan is adequate to draw air through collector.
i. Low pressure drop typically in the range of 32 to 52 Pa while heating air through large temperature rise, of 30 to 53°C, in a once through mode which allows maintaining low air flow rates and small passage length.

CONCLUSION

A novel 5 m^2 Solar Aluminium Tubular Air Heater, SATAH is developed. Typical day's test results of SATAH for 6 h average working are reported. Ambient air is heated in a once through mode from 33.3°C to 82.6°C with an average efficiency of 75.3%, when solar insolation on collector plane is 891W/m^2. Average mass flow rate of air for 6 h period was 13.8 g/s.m^2. Air circulation fan is operated by solar power which automatically modulates the air flow as the incident solar insolation varies. Total heat input to the collector in terms of solar radiation for 6 h period was 26.5 kWh or 5.3 kWh/m^2 and heat delivered was 19.9 kWh or 4.0 kWh/m^2 in terms of hot air. Weight of the collector is 38 kg or 7.6 kg/m^2 and the collector cost is about INR 1,420/kWh.d^{-1} (USD 22.8/ kWh.d^{-1}). Pressure drop across the collector was 50 Pa. This pressure drop is further reduced to 16 Pa in next generation SATAH which are currently under testing. The power consumed by a DC fan to circulate air through the 5 m^2 collector is only 32 W. Pay back realised is less than one year compared against heating up air using electricity.

REFERENCES

[1] ASHRAE Fuddamentals, 1997
[2] Duffie J A and Beckman W A, 1991, Solar Engineering of Thermal Processes, *2nd edition, Wiley USA*
[3] Garg H P and Prakash J, 2002, Solar Energy: Fundamentals and Applications, *Vol-II*, *Tata McGraw Hill*, *New Delhi*, 164 -171
[4] Janjai S, Esper A, MuÈ hlbauer W, 2000, Modelling the performance of a large area plastic solar collector, *Renewable Energy*, 21, 363-376
[5] Popel O S, Prokopchenko I V, Mordynskii A V, Frid S E, Ryzhikov I A, Ilyin A S, Lapin R S, 2008, Experience with development of solar collectors made of heat-resistant plastics, *Thermal Engineering*, 55, 12, 993-996
[6] Rane M V, 2004, Solar flat plate fluid heating device, Indian Patent, 234778
[7] Rane M V and Joshi S M, 2011, Plastic solar air heater for low temperature applications, *Proceedings of 4th International*

Conference of Advances in Energy Research, IIT Bombay, ICAER 2011.

[8] Rane M V, Mehta J R and Joshi S M, Solar collectors for low temperature applications, *Article in SME CONNECT Monthly Magazine*, Vol 1 Issue 4, Dec 2011, PP 44-50

[9] Sukhatme S P and J K Nayak, 2008, Soar Energy, Principles of Thermal Collection and Storage, *3rd Ed, Tata McGraw-Hill Publishing Limited (New Delhi)*