Performance Enhancement of Solar Water Heater using Compound Parabolic Reflector and Numerical Simulation of Thermal Losses

Rijo Cherian
M. Tech (Thermal Engineering), Department of ME
College of Engineering, Adoor
Kerala, INDIA
rijocherian797@gmail.com

Lasithan L G
Assistant Professor, Department of
ME College of Engineering, Adoor
Kerala, INDIA
lasithanlg@gmail.com

Abstract—**The purpose of this project is to design, fabricate and test the performance enhancement of a SWH with compound parabolic reflector (CPR). The advantage of this system is that there is no need of a sun tracker. Firstly, the experimental work is done by comparing the performance of two evacuated tube collectors, out of which one is equipped with a CPR at the bottom surface. Secondly, an ANSYS simulation is done to find the effect of thermal loss on the performance of the system. For almost all of the SWH which are commercially available, only the top portion of the evacuated pipe is used for absorbing the solar radiation. The shaded portion remains unused. A CPR uses a mirror in the shape of a compound parabola to reflect and concentrate sun radiations towards a receiver tube located at the focus line of the compound parabolic reflector. Thus the whole cylindrical surface of the evacuated pipe is made useful and the absorber surface absorbs the incoming radiations and transforms them into thermal energy. Thermal losses will occur mainly due to radiation and even though the system uses an evacuated tube collector, a small amount of loss occurs due to convection. Thus a thermal loss analysis around an evacuated tube collector is performed.**

***Index Terms*—Compound parabolic reflector, evacuated pipe, thermal loss.**

I. Introduction

Over exploitation of Conventional energy sources result in their rapid depletion. So the researchers are concentrating more on unconventional energy sources. Conventional energy sources are available from certain concentrated regions so there is always a possibility for shortage, especially when the demand exceed the supply. Sometimes this result in increase in the price. This shows the need for unconventional energy sources. Technologies utilizing renewable energy sources differ significantly from one another, not only with regard to technical and economic aspects but also in relation to their reliability, maturity, and operational experience in utility scale conditions. Solar energy harnessing technologies have emerged as the most promising and mature since solar energy is abundant, freely available, and it has commercial potential too. The aim is to increase the performance of solar water heater with less cost.

A lot of research works have been reported in the literature on solar-thermal systems. Kalogirou [1] conducted an exhaustive review on different types of solar thermal collectors and their applications. The various types of collectors were discussed and presented with their optical, thermal and thermodynamic analysis. Barlev [2] presented a review on concentrating collectors, viz. parabolic trough collectors, heliostat field collectors, linear Fresnel reflector, parabolic dish collector etc. They suggested that concentrated solar power (CSP) technology could not only be used for electricity generation, but also for large range of other applications such as desalination of water, industrial heating and cooling, detoxification and disinfection of water etc. Flat-plate collector and evacuated tube collector are mainly used to collect heat for low temperature applications. However, the latter has better performance and lower cost than the former. Recently, the market of the evacuated tube solar water heater has been expanded by the development of low cost sputtering technology for producing the absorber surface on all-glass evacuated tubes [3]. In China, solar thermal conversion systems have been studied for more than 30 years. During the last decade, the solar thermal industry has developed rapidly. By the end of 2012, around 257,000,000 m^2 of solar water heaters (SWHs) were in use in China, 90% of which were water-in-glass evacuated tubes SWHs [4]. The experimental work by Sakhrieh and Al-Ghadoor in the Jordanian market indicated that evacuated solar collectors had the highest efficiency of five types of solar collectors [5]. Hayek compared two types of evacuated tube solar collectors, and the results showed that heat-pipe-based collectors performed better than the water in-glass design, but the payback periods for water-in-glass collectors were relatively short [6]. A CPR can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any entering radiation within the collector acceptance angle will find its way to the absorber surface located at the bottom of the collector. As a kind of highly efficient moderate temperature solar collector, CPR solar collector has been widely studied in the design and analysis [7,8].

II. THE SOLAR COLLECTOR

The Heat Collection Element (HCE) consists of absorber tube surrounded by a glass envelope. The absorber region is coated with copper. The glass is coated with anti-reflective coating to reduce reflective loss. The annular gap between glass envelope and steel absorber tube is separated with a vacuum pressure in order to reduce heat losses as well as protecting the selective coating from degradation. The heat transfer model is based on the energy balance between heat transfer fluid and the surrounding.

Heat is dissipated to the ambient by means of convection and radiation losses. The convection heat transfer can be of natural or forced convection. The mode of convection depends on the wind condition at the collector surrounding.

$$= h \; (-)$$

The convection heat transfer coefficient of air can be calculated by using Mullick & Nanda correlation which is given by:

$$h = 4 \; {}^{-0.42} \; {}^{0.5}$$

Heat transferred by radiation from the glass envelope to the ambient can be calculated by:

$$= \; ({}^{4} - {}^{4})$$

The total heat loss is given by

$$= +$$

Where,

- h_a convection heat transfer coefficient of air (W/m^2K) D_g glass envelope outer diameter (m)
- T_g glass envelope outer surface temperature (K) v_w wind velocity (m/s)
- σ Stephan – Boltzman constant (5.67×10^{-8} W/m^2K^4) ρ density (kg/m^3)
- C_p specific heat capacity (W/kg-K) K Thermal conductivity (W/m-K) ε_g glass envelope emissivity
- T_a ambient temperature (K)
- Q_{conv} Heat loss by convection per unit length, (W/m)
- Q_{rad} Heat loss by radiation per unit length, (W/m)

III. CFD MODELING

Model of is designed in SOLIDWORKS 2015 as two concentric cylinders. The inner cylinder of diameter 0.036m and outer hollow cylinder of inner and outer diameters 0.037m and 0.038m respectively, was modeled. Once the receiver has been modeled, the model is then exported to CFD for meshing. Proximity and curvature meshing was done. After the meshing is completed, the domains are defined as fluid or solid according to their respective condition. The inner cylinder was defined as fluid and outer hollow cylinder as solid. The continuum volume of fluid region was defined as water. The solid region material was assigned as copper. The properties for the materials used is shown in Table 1.

TABLE I. PROPERTIES OF MATERIALS USED

Material	Density	Specific heat	Thermal conductivity	Viscosity
	kg/m^3	J/kg-K	W/m-K	Kg/m-s
Water	998.2	4182	0.6	0.001003
Pyrex	2225	835	1.4	
Copper	8978	381	387.6	

Meshing is a process whereby the model domain is divided or discretized into a finite number of smaller elements.

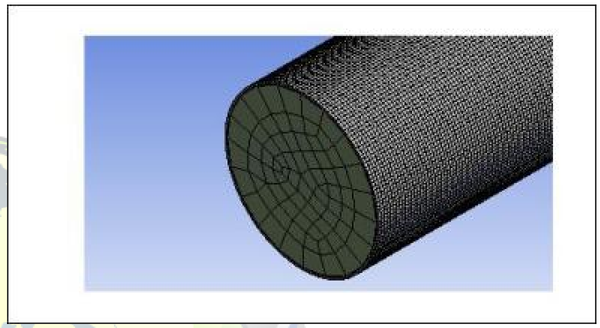

Fig. 1. Meshed model of copper pipe with water inside

TABLE II. PROXIMITY AND CURVATURE MESH DETAILS

MESH	DETAILS
Nodes	663760
Elements	335956
Minimum Orthogonal Quality	8.24785e-01
Maximum Ortho Skew	1.75215e-01

A. Boundary Conditions

The inner surface of the absorber tube is modeled as stationary with no – slip condition. The two surfaces of side walls of the absorber tube are modeled as adiabatic or zero heat flux condition. The outer surface of the absorber tube is modeled as non – zero heat flux condition. The effective incoming solar radiation is modeled as heat flux at the outer absorber tube. Heat flux on top portion of the outer absorber tube is assumed constant.

B. Analysis

A CFD transient analysis with flow time of 600s (10min.). The simulation analysis was done for various heat flux and the result was compared with the experimentally tabulated values. The analysis was done continuously with varying heat flux (every 10 min.) so as to duplicate the real-life scenario.

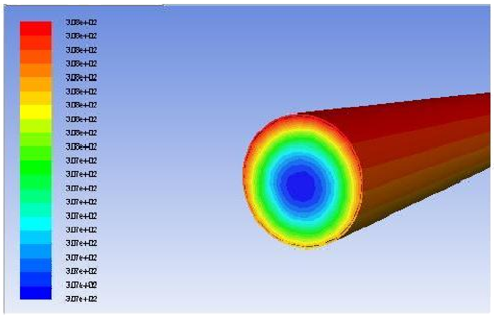

Fig. 2. CFD analysis temperature contour for a heat flux of 290W/m^2

TABLE III. EVACUATED TUBE COLLECTOR SPECIFICATION

Tube Length	1.5m
Outer Tube Diameter	0.047m
Inner Tube Diameter	0.037m
Tube Thickness	0.01m
Tube Material	Borosilicate Glass
Absorber material	Copper
Thermal Expansion	3.3 x 10^{-6}
Absorption Efficiency	> 92%
Emittance	< 8%
Vacuum Pressure	< 5x10 -3 Pa
Heat Loss	< 0.7 W/m^{2}C
Maximum Strength	1.0 MPa
Stagnation Temperature	> 428 °F

IV. EXPERIMENTAL WORK

The experimental setup consists of 4 evacuated tube and a storage tank. The evacuated pipe is a water in glass type tube collector. The specification of the evacuated tube collector is shown in Table II. The temperature readings were taken at the top portion of the evacuated pipe. The temperature readings were taken using a digital thermometer (FLUKE 1552A Ex STIK THERMOMETER). The solar radiation was measured using a SOLAR POWER METER(KM-SPM-11).

Fig. 3. Experimental Setup

TABLE IV. EXPERIMENTAL AND NUMERICAL OBSERVATIONS

HEAT FLUX	TEMPERATURE	
W/m^2	Experimental Temp (K)	Numerical Temp (K)
290	310.87	308
508	314.12	311
780	316.98	315
880	317.06	319
926	323.89	325
940	326.84	331
940	329.9	336
940	331.23	342
950	333.21	347
960	335.96	353
960	338.58	358
960	341.31	365
970	344.85	371
980	349.23	377
980	354.25	383
980	360.55	390
980	366.55	396
980	369	402

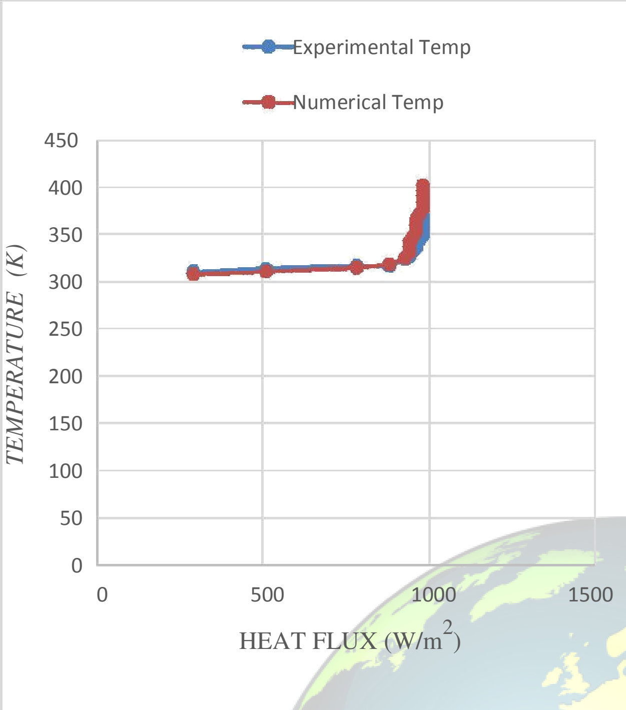

Fig. 4. Experimental VS Numerical

The experimental result was compared to the numerical result and it was found that the is a slight variation of the actual experimental work from the numerical simulation. The deviation it maximum at higher temperature and heat flux because,

1) The experimental setup use solar radiation as input which continuously vary over a range of values while the numerical simulation uses constant heat flux as input.

2) The thermal losses increase with increase in temperature and heat flux.

V. COMPOUND PARABOLIC REFLECTOR

The compound parabolic reflector(CPR) consists of a glass cover, an absorber tube and two parabolic reflecting surfaces.

The two parabolic reflecting surfaces 'A' and 'B' have their focal points lying on each other. The absorber tube is placed at the mid plane between the two focal points. If the angle of incidence is less than half of the acceptance angle, the solar radiation will pass through the receiver opening. If the angle of incidence is greater than half of the acceptance angle, the solar radiation will ultimately be reflected back to the ambience through the upper opening(aperture).

and readings were taken at a regular interval of 10min. Both the evacuated tubes were filled with water and placed in an inclined stand. The temperature readings were taken using a digital thermometer. The solar radiation was measured using a SOLAR POWER METER

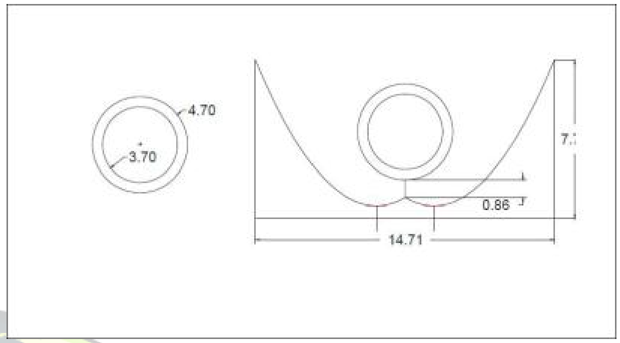

Fig. 5. CPR design

Fig. 6. Performance enhancement test setup

A. *Performance Enhancement test*

Performance enhancement test is conducted using two evacuated tube collector one with a compound parabolic reflector at bottom side. The experiment was started at 10.15am

TABLE V. EVACUATED TUBE COLLECTOR WITH AND WITHOUT CPR

Time	Heat Flux	TEMPERATURE	
	W/m^2	*EVACUATED TUBE (K)*	*EVACUATED TUBE WITH CPR (K)*
10.15am	265	305.82	305.82
10.25am	315	310.87	311.6
10.35am	700	314.12	315.45
10.45am	860	316.98	320.1
10.55am	900	317.06	322.05
11.05am	952	323.89	333.5
11.15am	940	326.84	345.33
11.25am	940	329.9	351.2
11.35am	940	331.23	363.85
11.45am	960	333.21	369.08
11.55am	960	335.96	369
12.05pm	960	338.58	369
12.15pm	960	341.31	369
12.25pm	980	344.85	369
12.35pm	980	349.23	369
12.45pm	980	354.25	369
12.55pm	980	360.55	369
01.05pm	980	366.55	369
01.15pm	980	369	369

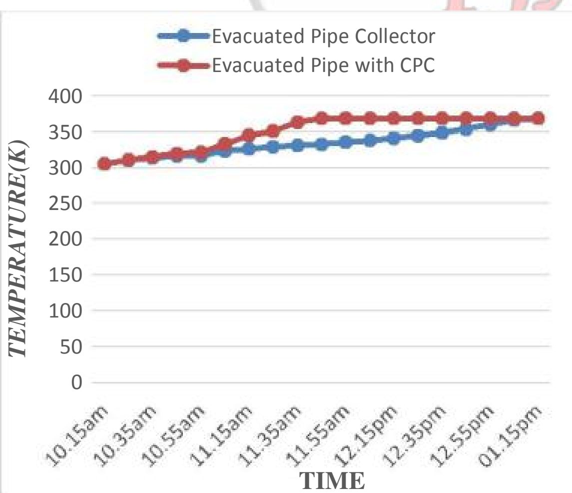

Fig. 7. Comparison of CPR with normal collector

VI. THERMAL LOSS TEST

The thermal loss test is done to find the effect of radiation and convection on the performance of the system. Ansys Structural was used for this analysis. The boundary conditions were applied considering the ambient temperature to be 27^0C. The convection heat transfer coefficient value at top surface of the evacuated tube collector is obtained using Nanda & Mullick correlation.

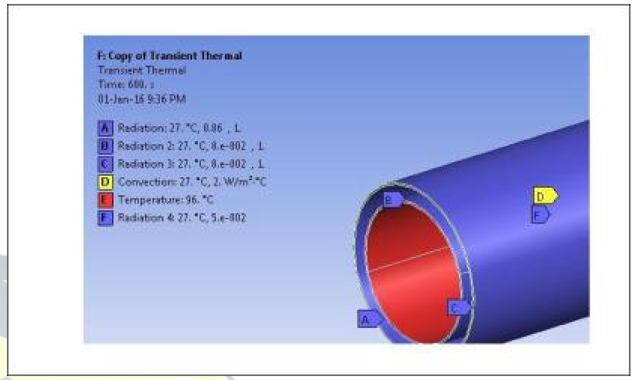

Fig. 8. Thermal loss test (Boundary Conditions)

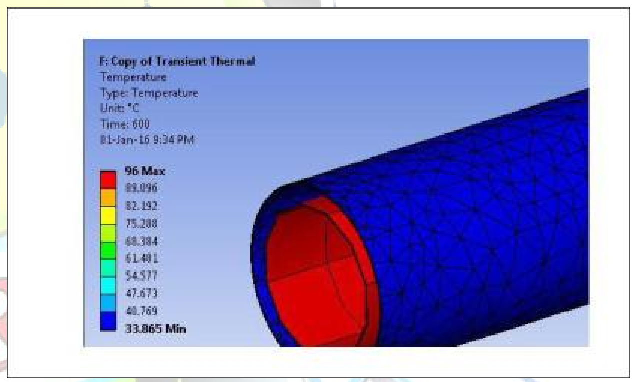

Fig. 9. Thermal loss test

The analysis was done and result was obtained. The result shows that the temperature on the outer glass cover will be approximately 34^0C. The result obtained is validated with the help a thermal imager.

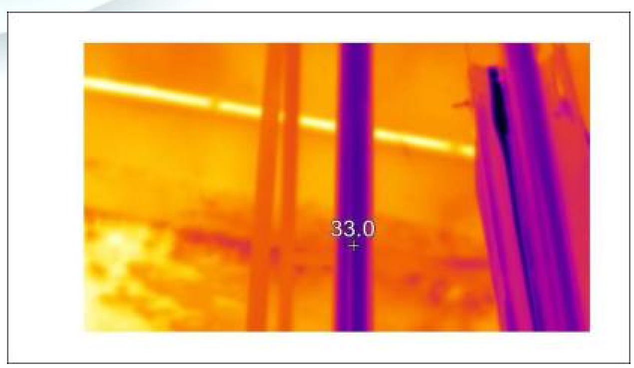

Fig. 10. Thermal images of Evacuated tube collector

VII. CONCLUSION

It can be seen clearly that the evacuated tube collector using CPR heats water to a higher temperature much faster than the normal evacuated pipe. The Heat Transfer Fluid (HTF) used is water so the highest possible temperature is 96^0C or 369K. The evacuated tube collector with CPR reaches the highest possible temperature within 90min. while the evacuated tube without CPR took more than 180min. Even though the compound parabolic reflector had some deformations (design was not accurate since it was handmade) a higher output was obtained. So it is of no doubt that a perfectly designed compound parabolic reflector will have a much better result. The thermal loss test shows that evacuated tube will help in reducing thermal loss the maximum outer cover temperature was 34^0C.

ACKNOWLEDGMENT

This work was carried out in CFD Research Laboratory, Department of Mechanical Engineering, College of Engineering, Adoor Kerala, India and is supported by TEQIP phase II.

REFERENCES

[1] Kalogirou SA. Solar thermal collectors and their applications. Prog Energy Combust Sci2004;30:231–95.

[2] Barlev D, Vidu R, Stroeve P. Innovation in concentrated solar power. Sol Energy MaterSolCells2011;95:2703–25.

[3] Tang RS, Li ZM, Zhong H, Qing L. Assessment of uncertainty in mean heat loss coefficient of all glass evacuated solar collector tube testing. Energy Convers Manage 2006;47(1):60–7.

[4] Zhentao L, Zhichen H, Guangming X. Development report for Chinese solar thermal industry (2011–2012), Sol Energy 2013; 1: 7–10.

[5] Sakhrieh A, Al-Ghandoor A. Experimental investigation of the performance of five types of solar collectors. Energy Convers Manage 2013;65:715–20.

[6] Hayek M, Assaf J, Lteif W. Experimental investigation of the performance of evacuated tube solar collectors under eastern Mediterranean climatic conditions. Energy Procedia 2011;6:618– 26.

[7] Winston R. Principles of solar concentrators of a novel design. Sol Energy 1974;16(2):89–95.

[8] Rabl A. Solar concentrators with maximal concentration for cylindrical absorbers. Appl Opt 1976;15(7):1871–3.