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Research Article

CFD Analysis of Cubical Receiver Solar Water Heater with Concentrated Collector

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Abstract

Solar water heaters are used to heat water for various purposes in domestic and commercial applications. In the domestic field, heated water is frequently for bathing, medicinal use, washing clothes. There are various ways to improve the performance of solar water heaters. To make conventional heating systems electricity free, solar energy is a very good option. By use of concentrating collector for solar irradiations, water is heated inside the absorber. In solar heaters, concentrating collector with cubical receiver is new approach of minimizing cost and reduces the conventional space consuming solar water heaters. Concentrated collector is a part where lots of work is possible. The efficiency of the heater depends on various parameters such as solar irradiation available, flow rate, initial temperature etc. Present paper discusses various apparatus setups and ways to improve efficiency by various means.

Keywords: *cfd analysis, concentrated collector, design, performance, solar water heater.*

1. Introduction

In India, generally electric current and fossil fuels are used heat the water. But these methods consume more electricity and/or conventional fuel in the form of wood or kerosene which is bit costly compared and moreover causes various pollutions. In general, hot water used in a general family, consumes 25% of total energy consumption of that family. These difficulties can be overcome by the efficient use of solar water heating. Various researchers studied for solar energy heating in commercial and household scenario; in this paper new design for receiver with collector is discussed and experimental work is done on collector solar water heater. We have used CFD method to judge the performance of water heater (Sukhatme S.P.).

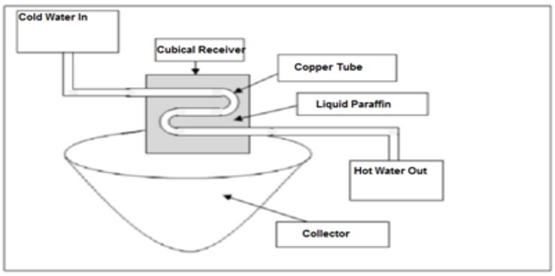

Fig.1. Schematic setup of solar water heater

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In proposed work, solar water heater collector focuses on the receiver tubes, which are painted with highly absorptive black color to maximize heating effect. The receiver tubes flow inside a cubical collector thus containing a working fluid medium with high heat conductivity.

Fluid is circulated inside can be changed and in this study it is liquid paraffin. This solar water heater can be used to obtain high outlet water temperature.

2. Aim

a. Analytical design of parabolic collector and cubical receiver by calculating heat loss for during the heating process.
b. Design CAD geometry for receiver parts and select best by analyzing selected receiver by using liquid paraffin at fixed temperature and flow.
c. Evaluate CFD results by studying with the help of experiments to validate the findings.

3. Literature survey

Abdullah et al. (2004) experimented on not glazed solar water heater having a storage system integrated within it and it was a non-metallic type of solar water heater. Reinforced Polyester of fiber is a GFRP and was collector material. Collector was used with 19 unglazed a half elliptical dimension with inclination was 150 to vertical. Hotel-Whillier-Bliss equation was used to calculate performance. Souliotis et al. (2006) worked on integrated collector storage (ICS) solar system having two storage water tank systems. They focused on cold weather condition for ICS and extended their research on flat plate. They used parabolic compound collector along with two horizontal cylindrical tanks. They used inverted absorber concept for better heating with different intensity solar radiations. Al-Madani (2006) studied the parameters varying the performance of solar water heater. He designed system for solar heater at low cost and for reducing electricity bills. In his work, solar heater used consist of cylindrical glass tube acts as receiver while copper coil painted black acts as collector mounted inside glass tubes. Missirlis D et al. (2012) studied modelling of solar collector using polymer material. He discussed changes in collector performance due to change parameters such as rate of fluid flow, solar intensity, and temperature at inlet and outlet and environmental changes etc. He used polymer material to reduce weight for cost effectiveness and compact size along with use of the honeycomb structure to minimize pressure drop.

Generally solar heaters with parabolic collector and flat plate are studied intensively. Cubical shaped receiver is new design which can prove to be shrewd one as it is expected to achieve and succeed high end results compared with conventions water heaters

4. Design for parabolic collector and receiver box

4.1 Design of collector

Concentrated collector in solar water heaters is used to concentrate the solar energy and are classified into two categories firstly line focused and secondly point focused. In line focused and point focused collector, amount of heat collected to heat the water varies due to amount of area available for focusing. Following paper reviews deals with design of solar water heater with concentrated collector to optimize performance of solar water heater. It was based on the effective area available for collector to absorb the solar radiations. The effective area is calculated by taking average solar intensity available for use was 750 W/m^2 for April month. And as average family used of 4 members use 60 liters of water (Mohammed I.L2012)which gives amount of heating required for water at normal temperature of 27^{0}C to heat to the temperature of 55^{0}C(Hussain Al-Madani2006).

Parabolic concentrator so it generates very high amount temperature heats receiver part. Liquid paraffin can sustain at such a high temperature as its boiling point is more than 800°C.

$$Q = m \times Cp \times \Delta t \quad (1)$$
Q = 0.00281 × 4.187 × 28
Q = 318.72 Watts

Area of collector Ae is given for Aluminium material having high reflectivity ρr of 0.818(Santosh K. Singh *et. al.* 2012).

Q = Rb × Ib × ρb × η × Ae (Hussain Al-Madani 2006)

318.7 = 750 ×0.818× 0.3 ×Ae
Ae = 1.6578m2

Thus this area is assumed circular in shape to find out diameter, which comes as 1.45 m.

4.2 Design of receiver

Receiver area is designed by using experimental trails on two plywood sheets which are placed one flat and other perpendicular to it such that the position inside collector is used to measure correct area of receiver. The actual area burnt during this process calculated approximately as 200 mm× 200 mm× 200 mm. Due to feasibility during fabrication, length of tube inside the receiver is kept constant so as to round up calculation.

5. Modeling of receiver

CFD analysis is done with the help of ANSYS 14.5 and CAD geometry is generated by using CATIA V5 R16 as standard tool for modeling. The variables which are governing current case are the diameter of the copper tube and its geometrical variations. Copper tube is fixed inside the receiver box at a specific angle made with the box. Therefore three different models of receivers are designed with different angle of tube with receiver box angle of inclinations as 3^0, 4^0 and 5^0(Abdullah S. et al. 2004). For sample only 1 model of receiver having 3^0 of inclination and 12mm diameter tube is shown. So in total there are nine models for 3 different copper tube diameters with 3 different angles of inclination. Figures below shows the copper tube inside cubical receiver is designed using CATIA v5 in 2D and imported 3D model inside ANSYS.

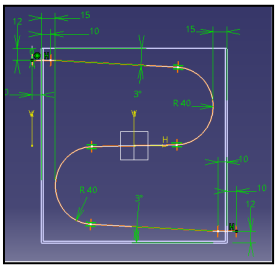

Fig.2 2D model

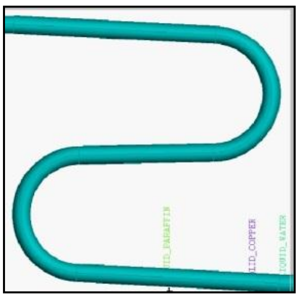

Fig. 3 3D model

6. Meshing of models

Volume meshing is done in ANSYS ICEM CFD 14.5 with prism layers. In following figure showing meshed copper tube as well as surface mesh is displayed.

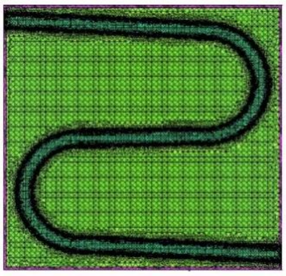

Fig.4. Meshing of model 1

Minimum mesh quality required is 0.2; hence for manual setting for minimum quality check 0.4 quality is set. Also quality check for each model is done by using tool. All nine models are meshed with approximately same number of mesh elements which can be served as mesh independency criteria (Natarajan M.et.al., 2014).

7. Fabrication of collector and receiver for solar water heater

7.1 Fabrication of collector

Collector was designed by using standard parabolic equation and fabricated with the help of square c.s. steel strips to make frame and aluminium sheets with 0.35 mm thick sheets which are highly reflective with reflectivity of 0.8 (Santosh Kumar Singh, 2012). Collector was mounted with wheels to mobilize and was mounted with manual tracking system for receiving maximum amount of solar intensity as thermal sensors and tracking mechanism consume electricity and also adds to the cost of apparatus.

Parabolic collector is designed with parabola equation

$$X^2 = 4\times a\times y \qquad (2)$$

Fig.5 Fabrication of collector frame

7.1 Fabrication of cubical receiver

Receiver box is designed for absorbing nearly all amount of incident solar radiation and thus painted with black paint. The area of cubical receiver is 200 x 200 x 200 mm which is designed based on min. area required to absorb the solar energy is kept with equal sides for easy fabrication and made up of stainless steel material so as to make it corrosion resistant.

Fig.6. Black painted cubical box

Table 1 Material used for experimental work

Sr. No	Part	Material	Dimension(mm)	Thickness
1	Receiver	Stainless Steel	200×200×200	2
2	Receiver Tubes	Copper	20,16,12	1

8. Setup for solar water heater with concentrated collector

Setup consists of the collector in the form of concentrated parabolic shaped dish and cubical receiver which is black painted square box made up of stainless steel in order to absorb all incident radiation on it (Hussain Al-Madani 2006). The cubical box contains copper tubes which are bent in the form of "S" shape runs through the receiver body.

During experimentation, parabolic type of collector is used with cubical receiver for studying purpose. Modelling and CFD analysis by using ANSYS fluent is carried out on test models with various conditions. Highly reflective aluminium is used as sheets for making of collector with high reflective polish. Receiver in the form of cubical box is used to heat the fluid inside the tubes. Stainless steel material with black paint on outside, is used for receiver (Eltahir A. M., 2013). Black paint is used to absorb all possible amount of radiation fallen on the receiver.

Receiver body is filled with liquid paraffin at normal temperature and pressure and is subjected to high temperature. It is subjected to constant temperature heating with paraffin temperature subject to concentrated heat. Manual operated tracking system to track the sun is utilized as various lights and thermal sensors and tracking mechanism consume electricity and also adds to the cost of apparatus to reduce overall power input, manual tracking system is utilized (Santosh Kumar Singh 2012). Binder tool is available for different diameters but as in chosen model, 12 mm copper tube installed in box so 12 mm diameter assigned bender used to make "S" shaped copper tubes. Total length of copper tube purchased was 5 feet so as to maintain high accuracy.

Water is used at normal temperature at inlet and flows through the copper tube at 0.0028, 0.005 and 0.0094 kg/hr flow rates for standard practice (Hussain Al-Madani2006). Dimensions of receiver 200×200×200 are fixed. Due to feasibility during fabrication, length of tube inside the Receiver is kept constant so as to round up calculation errors further. The variables which are governing current case are the diameter of the copper tube and its geometrical variations. Two thermocouples are used at inlet and outlet to measure temperature with pressure gauges to note down pressure drop.

Fig.7 Experimental setup of solar water heater

9. Results of CFD analysis

The receiver model is designed in the CATIA software and then imported into ANSYS 14.5 fluent solver for simulation. Total numbers of iterations used are 525 in which for convergence in current problem, numbers of iterations used are 325 iterations with SIMPLE algorithm and in second step it uses MUSCL interpolation to converge solution for 200 iterations (Versteeg H).

Fluent solver is used with k-ω turbulence model which is accurate model. Temperature profile shows that it varies inside the copper tubes at each point as water is flowing inside (Natarajan M.et.al., 2014). Convection can be seen in both temperature and velocity profile as vortex is generated.

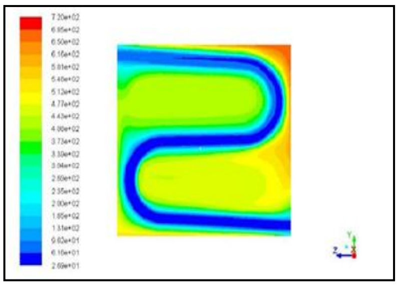

Fig.8 Temperature contour of model

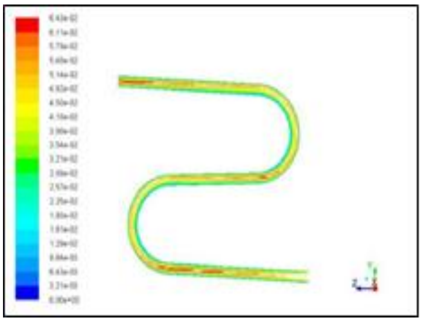

Fig.9. Velocity contour of model 1

10. Results of experimental analysis

Data provided by Indian Meteorological survey, Pune shows that solar intensity in April month per day was about 6.861 kWh/m^2. The experiment was conducted with three different water flow rates and paraffin liquid temperatures for time of 5 hours. The temperature of air surrounding the apparatus while conducting experiment approximately recorded to be 39^{0}C.

Table.2 Experimental results

Model No.	Mass Flow Rate (Kg/s)	Temperature at inlet (^{0}C)	Outlet Temperature (^{0}C)
1.	0.00281	28	67
2.	0.0052	28.2	51
3.	0.00943	27	40.2
4.	0.00281	27.2	94
5.	0.0052	29.2	67.2
6.	0.00943	29	50
7.	0.00281	31	108
8.	0.0052	30	78.2
9.	0.00943	31	56

11.Comparison of results

Data extracted from the CFD and experimental analysis shows that there are parameters depends on various factors and can be used to perform best output. CFD results when compared to the experimental data shows very less error, so we can say that experimental analysis can justify the CFD analysis we performed. CFD results are compared with experimental results in table below as it can be seen from table that, maximum of 9.2 % error is present between the both results which proves the feasibility of the solar water heater.

Table 3 Experimental procedure parameters

Receiver No.	Outlet Temperature (°C)		Percentage Error (%)
	By CFD	By Experiment	
1.	70.845	67	5.41
2.	51.621	51	1.23
3.	40.167	40.2	1.02
4.	103.154	94	8.874
5.	69.728	67.2	3.628

6.	49.721	50	1.04
7.	118.922	108	9.21
8.	78.564	78.2	1.2
9.	54.499	56	2.72

Conclusions

The present work shows that loss of energy between collector and receiver is due to convection and radiation heat loss. Heat loss between the two is mainly because of the temperature of liquid paraffin produced which is heated due to solar irradiations. Due to that, as temperature of liquid paraffin increases, directly affecting the percentage loss, which also increases along with rise in temperature. We have found by experiment that at about 70% of energy loss in the form of heat, takes place when temperature of inside the tubes for liquid paraffin becomes 300^0 C and more.

CFD simulations can tell that about 118^0C temperature at output can be generated with present set-up while practically only it reaches 108^0 C temperatures. Thus errors can be limited; in the validating results of CFD simulations are maximum 9.2% not more than that. To replace conventional energy sources for domestic water heating, use of solar energy looks very good alternative. Thus this project justified the use of solar water heater for household and commercial water heating purposes with much improved results and performance.

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