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THERMAL PERFORMANCE OF WATER-IN-GLASS EVACUATED TUBE SOLAR COLLECTOR WITH AND WITHOUT PHASE CHANGE MATERIAL

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ABSTRACT

Solar energy is one of the most significant renewable and alternative energy sources for several domestic and industrial applications. A simple and efficient approach to utilize solar energy is the direct conversion to thermal energy for various applications like water heating. Solar collectors are used to transform solar energy into heat energy in a Solar Water Heating System (SWHS). The present work has been initiated to study the possibility of storing solar energy using Phase Change Materials (PCMs) and utilizing this energy to heat water for domestic purposes during night time. In this paper, the performance of a water-in-glass evacuated tube solar water heater was investigated by three methods (i.e) without reflector, with reflector and with reflector cum PCM (Paraffin wax). Factors affecting the performance of water-in-glass evacuated tube solar collector tubes are discussed and a numerical study of water circulation through the tubes is presented. The simulation results were then compared with that of experimental results. It was found that the use of the suggested arrangement can result in 5°C to 7°C advantages in the stored hot water temperature over the extended periods of time.

KEYWORDS: Solar Water Heaters, Evacuated Tube Solar Collector, Natural Circulation, Thermal Performance, Numerical Simulation

The increase in the fuel prices, environmental pollution and the huge raise in green house gas emission are the main driving force behind the efforts for utilizing of different sources of renewable energy. As one kind of renewable energy, solar energy has received most considerable attention due to its ease of access and high potential in generating electricity and heat. The amount of sunlight falling on the planet at any one time is around 120,000 terawatts. If we capture a tiny fraction of 1% of this solar irradiance we are able to generate more power than the world's currently needs. Scientists have developed technologies in solar energy utilization, like electricity generation, hydrogen generation, solar heating and cooling, etc,.

The applications of solar energy to electricity generation and heat collection/refrigeration become important, and have received considerable attention. The solar collector is the heart of these solar energy utilization systems. During the last two decades a number of researchers have worked on developing new and more efficient solar collector or improving existing ones [Mills and Morrison, 2000] [Green M.A., 2004] [Goswami et. al., 2004]. Solar thermal collectors are devices which collect solar radiation, they transform it into heat and they deliver it to a heat exchanger through the heat carrier. This heat can be used to raise the temperature of the water that we use for cleaning, cooking and other processes. Solar-heated water can also be used for swimming pools, space heating and even to help cool buildings [http://www.powerfromthesun.net/Book/chapter06/chapter06].

Solar collectors can range from simple flat plate collectors with no glazing, to boxes or tubes covered with glazing, through to complex arrangements of mirrors. Solar collectors are usually found on the roofs of buildings but can also be fixed to vertical walls and balustrades or mounted on the ground. They are usually fixed to face in one direction but can also be fitted onto rotating tracking devices to follow the sun's movement across the sky. The main component of the solar water heating system is the solar collector. Basically a solar collector is a heat exchanger which converts the solar radiation into heat. The flat plate solar collectors are the most frequently used water heater for low temperature applications mainly water heating, because of their dependability, high thermal–hydraulic performances and also comparatively low price. The evacuated tube solar collectors have better performance compared to flat plate solar collectors, particularly for high temperature operations. On the other hand, the evacuated tube solar collectors are not the real competition for flat plate solar collectors, because of some difficulties in manufacturing and maintenance of the metal-to-glass vacuum seal.

LITERATURE SURVEY

A Solar Water Heating System (SWHS) is a device that makes the available thermal energy of the incident solar radiation for use in various applications by heating the water. Hot water is essential both in industries

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and domestic applications. It is required for taking baths, washing clothes and utensils, and other domestic purposes in both the urban and rural areas. Hot water is also required in large quantities in hotels, hospitals, hostels, and industries such as textile, paper and food processing, dairy, and edible oil. The SWHS consists of solar thermal collectors, water tanks, interconnecting pipelines, and the water, which gets circulated in the system. Figure 1 shows the typical thermosyphon solar water heating system [Ogueke et. al., 2009]. Solar radiation incident on the collector heats up the tubes, thereby transferring the heat energy to water flowing through it. In brief, solar energy incident on the flat-plate collector is absorbed by the black-chrome coated copper plate and thereby heats the water in the riser tubes which circulates due to density difference, i.e. the thermosyphon effect.

Solar Water Heating systems are grouped into two broad categories as passive and active solar water heating systems. The passive solar water heating systems generally transfer heat by natural circulation as a result of buoyancy due to temperature difference between two regimes; hence they do not require pumps to operate. They are the most commonly used solar water heating systems for domestic application. Active solar water heating systems have electric pumps, valves, and controllers to circulate water or other heat-transfer fluids through the collectors.

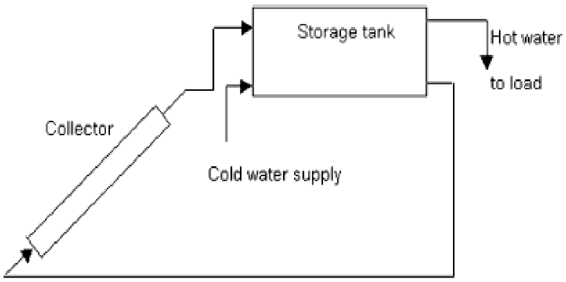

Figure 1: Schematic diagram of a typical thermosyphon solar water heating system

The active solar water heating systems generally have higher efficiencies, their values being 35%–80% higher than that of the passive systems [Ogueke et. al., 2009]. It is more complex and expensive. Accordingly, it is most suited for industrial applications where the load demand is quite high. On the other hand, the passive systems are less expensive and easier to construct and install which is more suitable for domestic applications where demand is low or medium. The characteristics of thermosyphon systems are based on the absorber plate and its design, selective coatings, thermal insulation, tilt angle of the collector, and working fluids, etc., Shariah et. al. [1999] have theoretically studied the effect of the thermal conductivity of the absorber plate of a thermosyphon solar water heater on the characteristic factors and solar fraction by the use of the TRNSYS computer program. Results were found that the collector efficiency factor and heat removal factor have strong dependence on the thermal conductivity of the absorber plate. Figure 2 shows the cut section of the flat plate solar water heater.

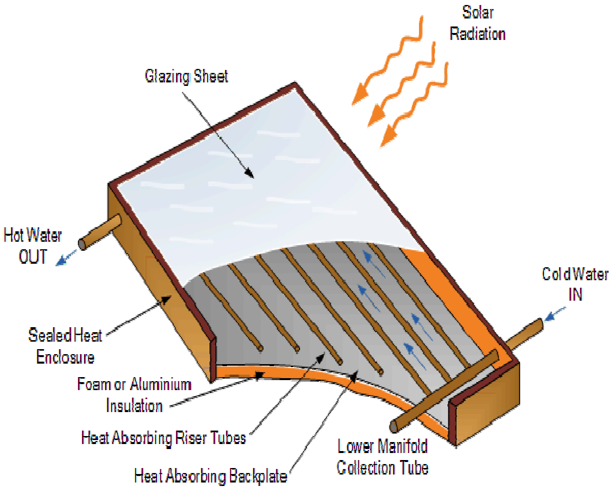

Figure 2: Flat plate solar water heater

Tang et. al., [2010] have constructed and tested two sets of thermosyphon domestic solar water heating systems to investigate the effects of water temperature in the storage tank in terms of outlet water temperature. Comparative studies have made on the thermal performance of water-in-glass evacuated tube solar water heating systems with different collector tilt angles by Tang et. al., [2011]. It was found to maximize the annual heat gain of such solar water heating systems, the collector should be inclined at a tilt-angle for maximizing its annual collection of solar radiation. Figure 3 shows the working principle of evacuated tube solar water heater.

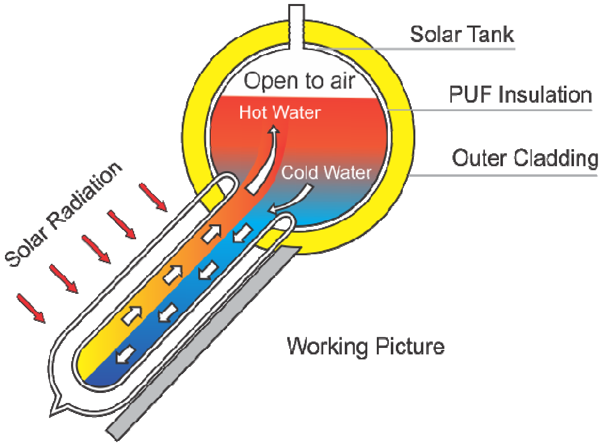

Figure 3: Evacuated tube solar water heater

Thermal energy storage systems which keep warm and cold water separated by means of gravitational stratification have been found to be attractive in low and medium temperature thermal storage applications due to their simplicity and low cost. This effect is known as thermal stratification. This system stores sensible heat in water for short term applications. Fath Hassan E.S., 1998 has reviewed the basic concepts, systems design, and the latest developments in the sensible and latent heat thermal energy storage. Vikram et. al., 2006 have studied the feasibility of storing solar energy using Phase Change Materials (PCMs) and utilizing this energy to heat water during night time. This ensures that hot water is available throughout the day.

A methodology is proposed by Kulkarni Govind et. al., 2007 to determine the design space for synthesis, analysis, and optimization of solar water heating systems. The proposed methodology was helpful in clear understanding of the behavior of the system with different storage volumes and collector areas. The thermo-hydrodynamic behaviour of the heat transfer fluid in a storage tank connected to a domestic solar collector was investigated by Alvarez et. al., 2013. A numerical simulation of the fluid inside the storage tank was performed in this research work using ANSYS Fluent as the simulation package. A 3D model of the collector involving the water pipe, absorber plate, the glass top and the air gap in-between the absorber plate and the glass top was modeled to provide for conduction, convection and radiation in the analysis [Vasudeva Karanth et. al., 2011] The numerical results obtained in this research work using Computational fluid dynamics (CFD) by employing conjugate heat transfer shown that the heat transfer simulation due to solar irradiation to the fluid medium, increases with an increase in the mass flow rate. Also they have found that the absorber plate temperature decreases with increase in the mass flow rate. Similar kind works were also found in the literatures [Turgut and Onur, 2009] [Selmi et. al., 2008].

Outcomes of Literature Survey and Research Gap

The following observations have been made after analyzing the papers from various reseach works. It is found out that the main applications of a solar collector is to produce hot water which is used for water heating, air heating, waste water treatment and other applications. Thermal performance of flat plate solar collector system with and without Phase change material has been done. Thermal analysis of Evacuated glass tube solar collector system with Reflector and Phase change material has not been attempted by many researchers. The main objective of this proposed work is the performance improvement of the Evacuated glass tube solar water heating system by applying Phase Change Material (PCM) as a latent heat energy storing material.

EXPERIMENTAL METHODS

Experiments were conducted on an evacuated tube solar collector exclusively developed for this research work during March and April 2017 at Salem, Tamil Nadu, India, The developed evacuated tube has the following technical specifications (Refer Table 1).

Table 1: Specifications of the evacuated tube solar collector

Outer Diameter of the tube	58 mm
Inner Diameter of the tube	47 mm
Glass thickness	1.8 mm
Length of tube	1.8 m
Selective coating type	AIN/AIN-SS/CU – Sputtering
Material of the tube	Borosilicate Glass 3.3
Thermal Expansion	3.3×10^{-6} / °C
Emission ratio	< 0.07
Vacuum	$P < 5 \times 10^{-3}$ Pa
Stagnation Temperature	>200 °C
Heat Loss Coefficient	$< 0.7\ 5\ w/m^2$
Inclination	17°
Mass flow rate	15 kg/hr
Ambient temperature	31- 34°C

Experimental setup is containing Evacuated glass tube collector with ten numbers of tubes, insulated hot water tank, reflector and Insulating box etc. The

Schematic diagram of the experimental set up is shown in Figure 4. The thermal Energy Storage tank is used to increase the performance of the system with the help of paraffin wax as a phase change material. Paraffin wax is used to store large amount of latent heat during its fusion. A schematic diagram of the experimental setup is shown in Figure 2. The setup is very much similar to conventional solar water heating systems available in the market with few differences. Borosilicate glass tube used in this research work has been coated with AIN/AIN-SS/CU through sputtering technique of 1.8 mm thickness with inner diameter 47 mm and outer diameter of 58 mm. A vacuum pressure less than 5 X 10^{-3} Pa has been maintained between the tube walls. The angle of inclination such as 17° of the evacuated tubes is considered with mass flow rate of 15 kg/hr. The ambient air temperature is as 31°C - 34°C. The collectors have black painted reflector plates placed at back of the evacuated tubes. The galvanized steel storage tank is cylindrical in shape having a volume of 75 litres. It is insulated with 25-mm thick layer of glass wool insulation.

The solar irradiation is measured by using a Pyranometer and the same is given in Figure 5. The ambient temperature, Temperature of water in and out were also measured and recorded. Wind flow meter is used to record the variations of the wind velocity during experiments. Figure 5 shows the solar irradiation measured on three different sunny days at Salem, Tamil Nadu, India. The average solar radiation is computed and the same is used for simulating the evacuated tube solar collector as the heat source for the numerical models.

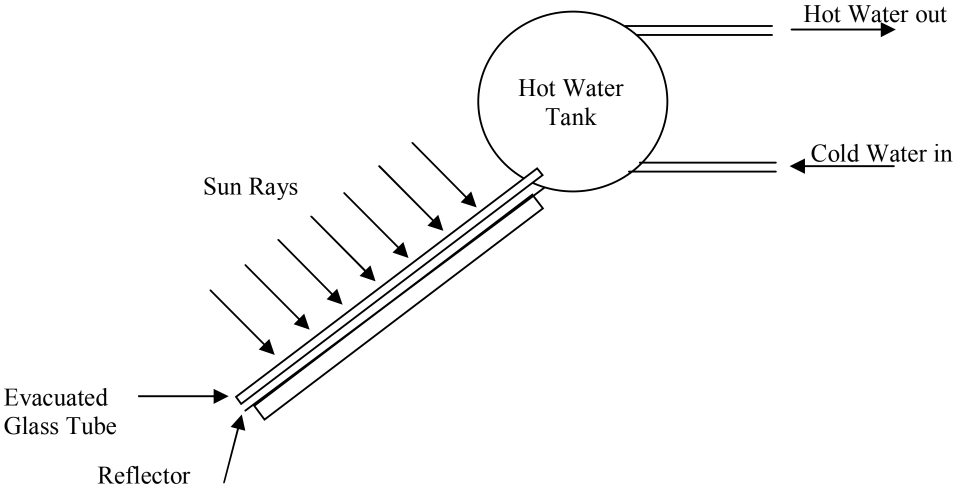

Figure 4: Schematic diagram of Evacuated Tube Solar Water Heater

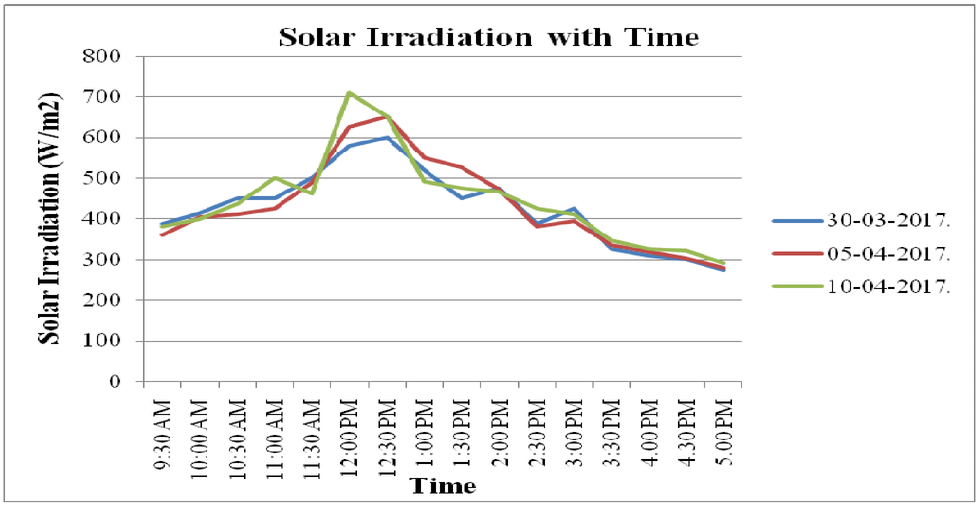

Figure 5: Solar irradiation values

Phase Change Materials – Latent Heat Storage Materials

Phase change materials (PCM) are ‘‘Latent’’ heat storage materials. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. This is called a change in state, or ‘‘Phase.’’ Initially, these solid –liquid PCMs perform like conventional storage materials; their temperature rises as they absorb heat. Unlike conventional (sensible) storage materials, PCM absorbs and release heat nearly at constant temperature. They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock. A large number of PCMs are known to melt with a heat of fusion in any required range. We added 27 kg PCM (Paraffin Wax) in PCM tank as 100 liter water requires 36kg of PCM. Table 2 shows the thermo-physical properties of the paraffin wax.

Table 2: Thermo-physical properties of the paraffin wax.

Sr. No.	Property name	Values
1	Melting point	58-60°C
2	Latent heat of fusion	190 KJ/Kg K
3	Density (Solid Phase)	820 Kg/m3
4	Density (Liquid Phase)	780 Kg/m3
5	Specific Heat	2.4 KJ/Kg K
6	Thermal Conductivity	0.24 W/mk

NUMERICAL ANALYSIS

Assumptions

1) The solar radiation intensity of the evacuated vacuum tube along the axial and circumferential directions is taking uniform.

2) The wind speed is in the normal direction and constant of the vacuum tube glass cover.

3) The working fluid givne in the tube is uniform and the flow is assumed to be constant.

4) The pressure, temperature and other parameters in the same section are uniform.

Objectives

The main objectives are:

1. To determine the efficiency variation in Evacuated tube solar system for three different conditions.

2. To analyze the thermal performance of Evacuated tube solar collector by inserting the Reflector below the Evacuated glass tube collector.

3. To analyze the performance of Evacuated glass tube solar water heating system by applying the phase change material as a latent heat energy storage material.

Methodology

The following methodology is preferable for the proposed work to achieve the above mentioned objectives:

1. Selection of input parameters for the evacuated tube solar collector system by literature survey.

2. To study the performance of evacuated tube solar collector system, i.e. thermal efficiency, collector efficiency, reliability, quality, durability and the conservation of energy.

3. Design and fabrication of the prototype Evacuated Glass Tube Solar Collector system to trsnsfer the heat to phase change material at maximum temperature.

4. Thermal analysis of the evacuated tube solar collector system in terms of useful heat gain, instantaneous hourly efficiency and overall thermal efficiency of the system.

5. Experimental validation, performance evaluation and selection of the best result for improved efficiency of the fabricated evacuated tube solar collector system.

Evacuated Tube Collector

Heat transfer analysis of the evacuated tube solar collector is performed through numerical analysis software COMSOL Multiphysics. Solid modelling of the glass tube, vacuum chamber, and water domain has been developed in CREO, a solid modelling package. These solid models were then exported in the form of .sat file, a neutral file for numerical analysis in COMSOL.

Figure 6 shows the solid models of an evacuated tube solar collector. Since the open end of the collector is connected directly to a storage tank, this opening serves as both the inlet for cold water to enter the collector (via the lower portion of the opening) and the outlet for hot water to exit (via the upper portion of the opening) the collector. The upper and lower half of the open end of the collector are modelled as outlet and inlet respectively. The evacuated glass tube material for the analysis is borosilicate glass with thermal conductivity 1.13W/mK. The boundary conditions for the heat flux through the wall of a cross section hollow cylinder operating with one steady state heat conduction surface temperature T_1= 304

K on the inner surface available at radial location r_1= 0.0235m, and a surface temperature T_2= 305 K is applied on the outer surface which is available at radial location, r_2= 0.029m.

The heat transfer equation is developed for solids and fluid as both involved in this problem. i.e, heat transfer in solid and heat transfer in liquid. The governing equations for heat transfer in solid and liquid are given in Equations (1) and (2).

Heat Transfer in solid

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P U.\nabla T = \nabla.(k \nabla T) + Q \quad \text{------ (1)}$$

Heat Transfer in Fluid

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P U.\nabla T = \nabla.(k \nabla T) + Q + Q_{vh} + W_P$$

------ (2)

Meshing of the finite element model is carried out to by auto-mesh option to discretize the domain in to small and manageable regions. Figure 7 shows the meshed model of the evacuated tube solar collector.

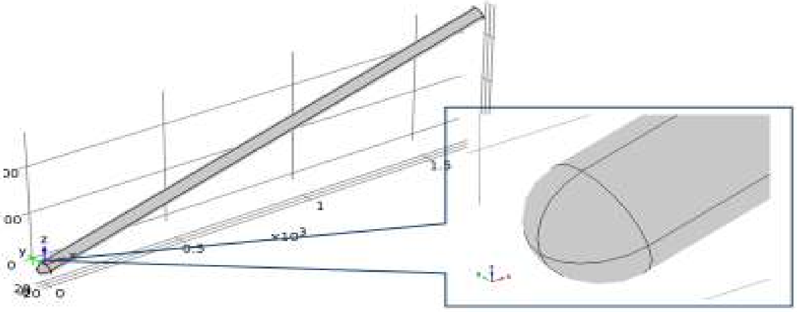

Figure 6: Solid Modeling of Evacuated Tube

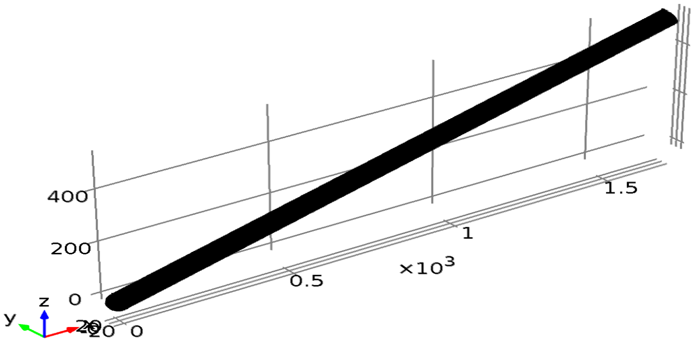

Figure 7: Meshed Model of the evacuated tube

RESULTS AND DISCUSSION

In the analysis of evacuated glass tube solar collector, the overall efficiency of the collector and heat gain by the water based on input and output parameters have been found out by three methods (i.e) without reflector, with reflector and with reflector cum Phase Change Material.

Analysis of Evacuated Tube Solar Collector without Reflector

In this analysis of evacuated glass tube solar collector, the overall efficiency of the collector based on input and output parameter was found out by the following method.

Efficiency = Output/ Input × 100.

Input = Intensity of solar radiation × Aperture Area = I_T × A

Output = Heat gain by the water = m×Cp×dT.

Specifications:

m = mass flow rate of water = 15 kg/hr.

Cp = specific heat of water= 4.187 kJ/kg K.

D= External diameter of Evacuated Glass tube = 58 mm= 0.058 m.

L= length of Evacuated Glass tube = 1800 mm= 1.8 m.

N= Number of tubes = 10 Nos.

A= area of Receiver Tubes = Tube diameter × Length of tube × No. of Tube.

= D×L×N = 0.058×1.8×10= 1.044 m^2

I_T = Intensity of Solar Radiation

By using the efficiency equation determine the efficiency at each hour.

$$\eta_{WO-Refl} = \frac{m \times C_p \times (T_0 - T_i)}{A \times I_T}$$

The efficiency of the collector without reflector was found out and it is given in Figure 8. From the calculations, the maximum efficiency was 63.06%. The maximum heat gained by the water is 348.92 W.

Analysis of Evacuated Tube Solar Collector with Reflector

The evacuated glass tube solar collector was modified by introducing reflector at the back of the evacuated glass tubes. Now the collector area is increased and that will be given by,

A= area of Reflector = width of reflector × Length of reflector.

= b×L = 0.895×1.8= 1.611 m^2

I_T = Intensity of Solar Radiation

$$\eta_{With-Refl} = \frac{m \times C_p \times (T_0 \quad T_i)}{A \times I_T}$$

The efficiency of the collector with reflector was found out and it is given in Figure 8. From the calculations, the maximum efficiency was 64.50%. The maximum heat gained by the water is 383.81 W.

Analysis of Evacuated Tube Solar Collector with Reflector and PCM

In this analysis total mass of water is given by,

m = mass flow rate of water = 15 kg/hr.

Cp = specific heat of water= 4.187 kJ/kg K

A = area of Reflector = width of reflector × Length of reflector

= 0.895×1.8= 1.611 m^2

I_T = Intensity of Solar Radiation at

$$\eta_{With\ Refl+PCM} = \frac{m \times C_p \times (T_0 - T_i)}{A \times I_T}$$

The efficiency of the collector with reflector and PCM storage was found out and it is given in Figure 8. From the calculations, the maximum efficiency was 66.71%. The maximum heat gained by the water is 401.25 W.

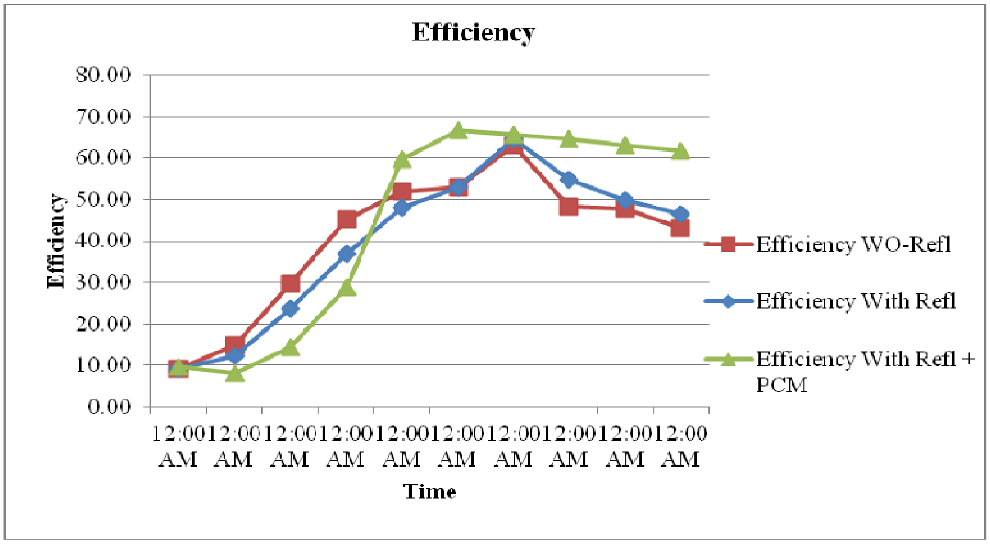

Figure 8: Efficiency with Reflector + PCM

Variation in Heat Gain

Figure 9 gives the values of heat gained by the water. It is almost directly proportional to hourly efficiency. Due to increase in hourly efficiency, the heat gained by the water also increases. Here heat gain by the PCM plays the important role for storing latent heat energy. Heat gain by water is given by $Q = m \times cp \times (To - Ti)$. From Figure 9, it is clearly found that heat gained by the water has the maximum value when the system provides with the reflector and the PCM.

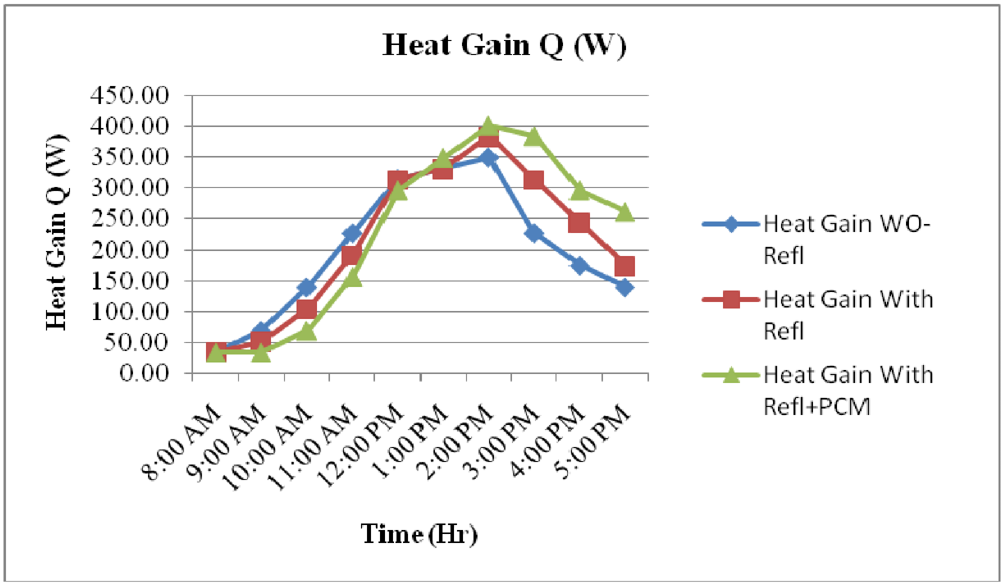

Figure 9: Heat Gain Values

CONCLUSION

The performances of water in glass evacuated tube solar collector have been analyzed in this paper by three methods (i.e) without reflector, with reflector and with reflector cum Phase Change Material (PCM). The PCM is used as a latent heat storage material. The following conclusions may be drawn as follows:

- The average efficiency of the conventional solar system is lower than that of the evacuated tube solar system with reflector based on the climate conditions and boundary conditions.
- The energy consumption of the system can be reduced by integrating with PCM as the latent heat storage device.
- The main advantage Evacuated Tube Solar collector is low heat loss at high temperatures relative to ambient temperature. The system gives more suitable output of result with respect to time.
- Phase change material is feasible option to increasing the efficiency of plant. So that hot water can be made available for longer time.
- It was found that the use of the suggested arrangement can result in 5°C to 7°C advantages in the stored hot water temperature over the extended periods of time.
- The efficiency of the system can be incresed from 63.06% to 66.71% and the heat energy gained by the water can be increased from 348.92W to 401.25W.

REFERENCES

Mills D.R. and Morrison G.L., 2000. Compact linear fresnel reflector solar thermal power plants, Solar Energy, **68**: 263–283.

Green M.A., 2004. Recent development in photovoltaics, Solar Energy, **76**: 3–8.

Goswami D.Y., Vijayaraghavan S., Lu S. and Tamm G., 2004. New and emerging developments in solar energy, Solar Energy, **76**: 33–43.

http://www.powerfromthesun.net/Book/chapter06/chapter06.html

Ogueke N.V., Anyanwu E.E. and Ekechukwu O.V., 2009. A review of solar water heating systems, Int. J. Renewable Sustainable Energy, **1**:043-106.

Shariah A.M., Rousana A., Rousanb Kh.K. and Ahmad A.A., 1999. Effect of thermal conductivity of absorber plate on the performance of a solar water heater. Int J Appl Therm Eng, **19**:733–41.

Tang R., Cheng Y., Wu M., Li Z. and Yu Y., 2010. Experimental and modeling studies on thermosiphon domestic solar water heating systems with flat-plate collectors at clear nights. Int J Energy Convers Manage, **51**:2548–56.

Tang R., Yang Y. and Gao W., 2011. Comparative studies on thermal performance of water-in-glass evacuated tube solar water heating systems with different collector tilt-angles. Int. J. Solar Energy, **85**:1381–9.

Fath Hassan E.S., 1998. Technical assessment of solar thermal energy storage technologies. Int. J. Renewable Energy, **14**(1–4):35–40.

Vikram D., Kaushik S. and Prashanth V., 2006. Nallusamy An improvement in the solar water heating systems using phase change materials. In: Proceedings of the international conference on renewable energy for developing countries.

Kulkarni Govind N., Kedare Shireesh B. and Bandyopadhyay S., 2007. Determination of design space and optimization of solar water heating systems. Int. J. Solar Energy, **81**:958–68.

Alvarez A., Baz M., Cabeza O., Ferrin J.L., Muniz M.C. and Varela L.M., 2013. Experimental and numerical simulation of a storage tank connected to a flat-plate solar collector, International Conference on Renewable Energies and Power Quality (ICREPQ'13) Bilbao (Spain), 20th to 22th March, 2013, ISSN 2172-038 X, No.11.

Vasudeva Karanth K., Manjunath M.S. and Yagnesh Sharma N., 2011. Numerical Simulation of a Solar Flat Plate Collector using Discrete Transfer Radiation Model (DTRM) – A CFD Approach, Proceedings of the World Congress on Engineering, Vol III WCE 2011, London, U.K.

Turgut O. and Onur N., 2009. "Three dimensional numerical and experimental study of forced convection heat transfer on solar collector surface", International Communications in Heat and Mass Transfer, **36**: 274-279.

Selmi M., Al-Khawaja M.J. and Marafia A., 2008. "Validation of CFD simulation for flat plate solar energy collector", Renewable Energy, **33**: 383-387.