An Experimental Study on Evacuated Tube Solar Collector using Therminol D-12 as Heat Transfer Fluid Coupled with Parabolic Trough

P.Selvakumar [#1], P.Somasundaram [#2], P.Thangavel [#3]

[#1] Department of Mechanical Engineering, Kongu Engineering College
Perundurai, Erode -638 052, Tamilnadu, India
[#1] kecselvakumarp@gmail.com
[#2] Department of Mechanical Engineering, EBET Group of Institutions
Kangeyam, Tirupur -632 108, Tamilnadu, India
[#2] somuannauniv@hotmail.com
[#3] Department of Mechanical Engineering, Kongu Engineering College
Perundurai, Erode -638 052, Tamilnadu, India
[#3] vptvel@gmail.com

Abstract— An evacuated tube solar collector using therminol D-12 as heat transfer fluid coupled with parabolic trough is studied in this paper. An experimental set-up was constructed to study the performance of evacuated tube collector with therminol D-12 as heat transfer fluid. The parabolic trough is coupled with evacuated tube collector for better performance. In the traditional solar collectors water is used as heat transfer fluid. The problems in using water as heat transfer fluid are addressed in detail in this paper. The temperature characteristics of heat transfer fluid and water in the storage tank and the heating efficiency are determined under various conditions. The efficiency of therminol based evacuated tube collector coupled with parabolic trough is 40% more than that of water based evacuated tube collector coupled with parabolic trough. This study projects the potential of therminol based evacuated tube solar collector coupled with parabolic trough in the instant hot water generation.

Keyword - Solar Collector, Therminol, Parabolic trough, Instant hot water

I. INTRODUCTION

The performance of evacuated tube solar collectors is better when compared to flat plate collector in high temperature applications. So, the evacuated tube is considered to be an important component in thermal application, particularly in solar water heating systems [1]. Different parameters like optical design, optimum operating conditions, heat transfer in tubes and performance studies of solar collectors have been studied by several researchers [2-10]. Extracting heat from the evacuated tube is a major difficulty in evacuated tube solar collector applications [4]. Various designs of heat extraction manifold have been developed for single ended evacuated tube. The fluid-in-glass and fluid-in-metal are the significant designs for better performance. Between the two, fluid-in-glass collector is widely used because of its low manufacturing cost and high thermal efficiency [1]. The fluid in the tubes is heated by solar irradiance. Water is used as heat transfer fluid by many researchers. Morrison et al. [4] studied the natural circulation of heat transfer fluid in fluid-in-glass evacuated tubes experimentally and numerically. Budihardjo and Morrison [5] studied the long-term performance of fluid-in-glass evacuated tube solar collectors with transient modelling. Fluid-in-glass evacuated tube cannot withstand high pressures and hence it is suitable for applications where few metres of water head is available.

Metal-in-glass collectors with heat pipe concept have been developed for high temperature and high pressure applications [3]. Azad [6,7] studied the thermal behavior of heat pipe solar collectors experimentally and theoretically. Higher thermal efficiency is achieved only, when the heat pipe is maintained in a proper vacuum environment [8]. Practically, it is difficult to maintain a good vacuum environment because of formation of non-condensable gas during the operating time. The operating life of the heat pipe will get reduced drastically due to improper maintenance of vacuum [9]. Sawhney et al. [2] developed the thermal performance model of evacuated tube solar collector with U-shaped fluid channel embedded in a flat absorber.

New technologies [11-13] have been developed to enhance the heat transfer from absorber tube to the working fluid. Most of the studies involve changing the structures of solar collectors, improving the absorptivity of the coating or reducing heat loss of the collector. Few researchers have studied the influence of working fluids on collector performance that too in industrial applications [14-16]. Solar collectors work satisfactorily when the working fluid temperature is greatly in excess of the normal boiling point of water. Water can be used as working fluid when the temperature is above 0°C and working pressure is high. Air standard cycle efficiency can be improved with the help of alternate heat transfer fluid. Ammonia or silicon oil can be used as heat transfer fluids. Ammonia is toxic and silicon oil can be preferred. Therminol D-12 oil is chosen as a heat transfer fluid in the present study because of its low viscosity. In this work parabolic trough is coupled with evacuated tube for better heat transfer enhancement and viscosity decrement. Parabolic trough design is adopted from the studies of Manoon et al. [17]. For instant hot water generation, people use fossil fuels in sub-urbans and cooking gas and electricity in urban areas. With the help of the present experiment, a new method is demonstrated for generating instant hot water.

II. THERMINOL AND ITS PROPERTIES

Fluids with low specific heat can have high heat gain from incident solar energy. Few researchers [14-16] studied the enhancement of performance of solar water heater by alternate heat transfer fluids. Selvakumar et al. [18] studied the heat transfer and fluid flow characteristics of various heat transfer fluids like helium, therminol, calfo, duratherm, exceltherm, molten salt, dynalene and vegetable oil. Therminol is suggested as the best heat transfer fluid for short flow length applications. Therminol is available in different grades and its selection depends on the safe operating temperature limits. Different grades of therminol and their working temperatures are shown in Figure 1.

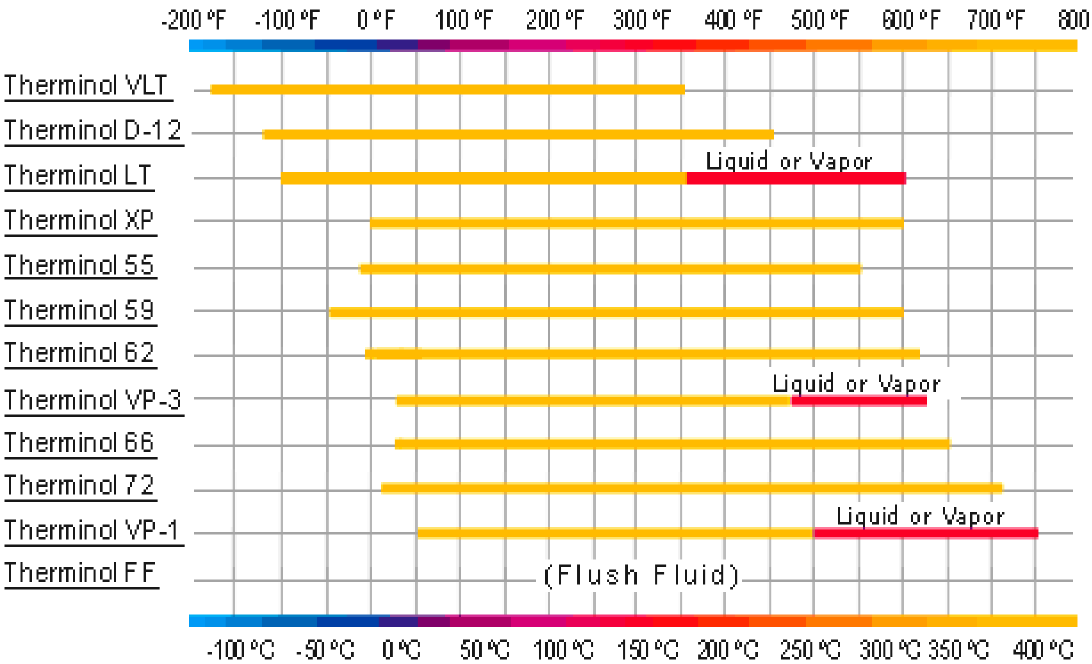

Figure 1 Therminol grades and operating temperature limits (Source:www.therminol.com)

Therminol-D12 which has flash point of 260°C and fire point of 267°C is an inexpensive and easily available heat transfer fluid. The other fluid properties like density and viscosity are close to that of water. The comparison of fluid properties of Therminol-D12 with that of water is shown in Table.I

TABLE I
Comparison of Properties of Therminol D-12 and Water

Properties	Therminol-D12	Water
Density	755 kg/m^3	1000 kg/m^3
Specific heat	2.5 kJ/kg K	4.186 kJ/kg K
Kinematic Viscosity	1.42 centi Stoke @ 20°C 0.66 centi Stoke @ 120°C	0.801 centi Stoke @ 30°C 0.294 centi Stoke @ 100°C

III.EXPERIMENTAL SET-UP

The experimental set-up which is shown in Figure 2 consists of a parabolic trough, an evacuated tube solar collector and a heat exchanger type storage tank. Two fluid flow circuits are employed in the set-up. One is therminol flow circuit and the other is water flow circuit.

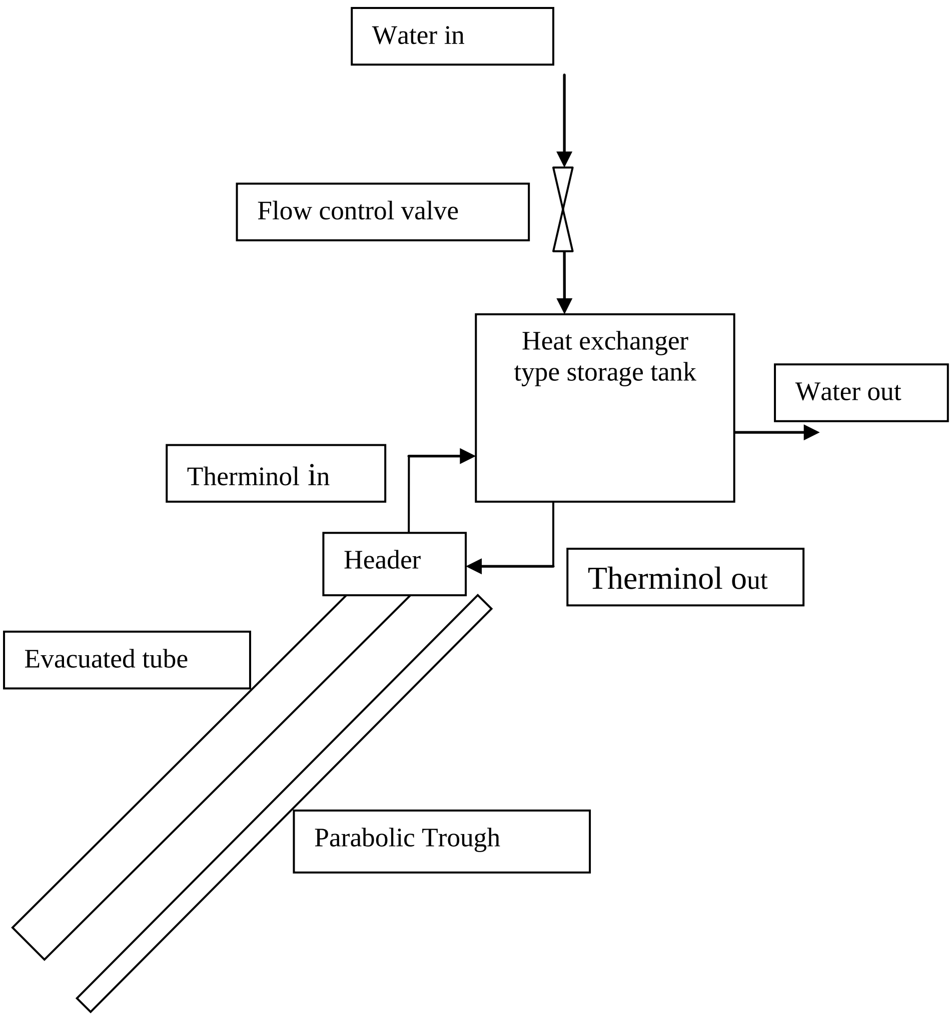

Figure 2 Schematic diagram of experimental set-up

A standard evacuated tube collector of length 1500mm and diameter 47mm is used in the set-up. Therminol D-12 oil is filled in the evacuated tube solar collector through a specially designed header. The header shown in Figure 3 has an inlet and outlet along with an oil hole and a safety valve. The outlet of the header is connected to one end of the passive heating coil placed inside the storage tank. The other end of the passive heating coil is connected to the inlet of the header. Thermosyphon flow is employed in the therminol flow circuit. The parabolic trough is fabricated by stainless sheet with a dimension of 1.2 x 2.4 m. Water is made to flow through inlet of storage tank and gets heated by the passive heating coil. The hot water is collected at the outlet of the storage tank. A flow control valve is provided at the inlet of the storage tank. Thermocouples are fitted at the outlets and inlets of header and storage tank. The required testing condition is the solar irradiance should be constant. The set-up is positioned in north-south direction. A similar type of experimental set-up with water as heat transfer fluid is also installed to study the comparison between therminol based system and water based system. For countries with tropical climatic conditions, the instant hot water requirement is more in the morning and evening hours particularly from the month of September to February. The study is carried out from September2012 to February2013. As the aim of the present work is to produce instant hot water in short duration, the experiment is conducted from 0700 hours to 0900 hours in the morning and 0400 hours to 0600 hours in the evening. The wind velocity varied between 2-3 m/s during the testing period. The convection effects are neglected during the calculations. The shadow effect caused by the tubes on parabolic trough is also neglected. Calibrated K-type thermocouples connected with data logger are used to record the temperature readings. Solar radiation is measured continuously with the pyranometer available in the solar radiation monitoring station.

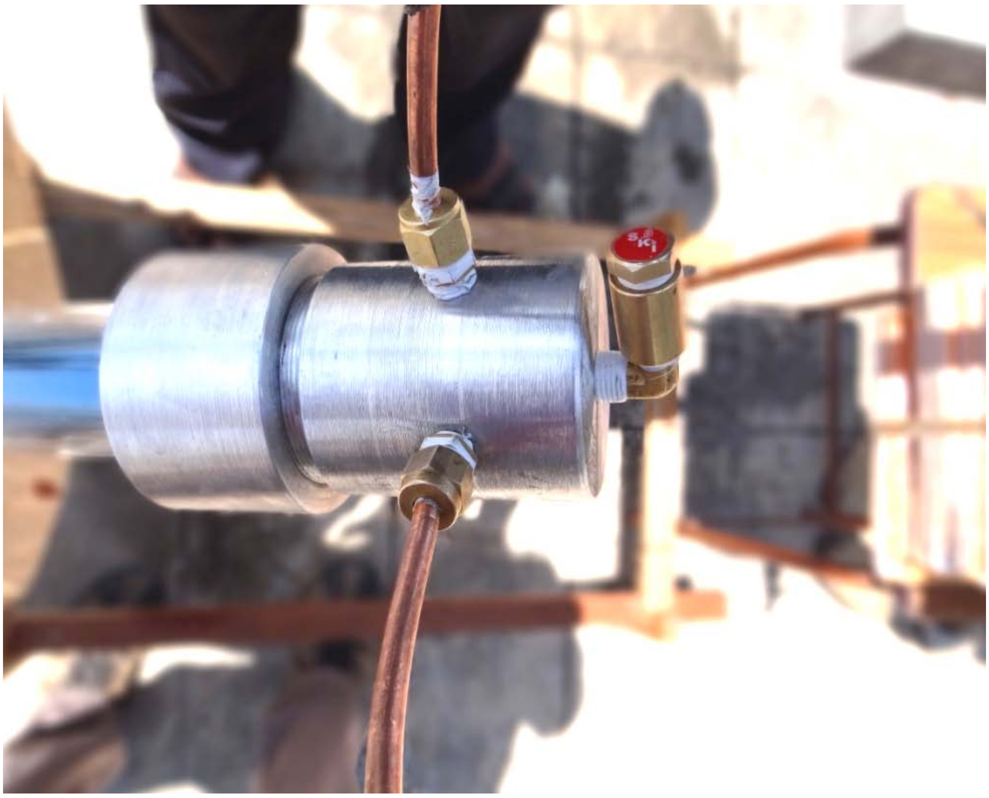

Figure 3 Photograph of header

IV. PERFORMANCE CALCULATIONS

The heat efficiency of the evacuated tube is defined as ratio of amount of heat energy absorbed by the heat transfer fluid to solar irradiance absorbed by the tube. The efficiency calculations for evacuated tube collector were studied by Ruobing Liang et al. [19]. The formula for calculating parabolic trough collector efficiency is reported by Li et al. [20]. In the present work, under steady state conditions, the heat absorbed by the heat transfer fluid will be equal to sum of direct solar radiance absorbed by the tube and heat reflected and emitted by the parabolic trough. The heat absorbed by the therminol oil is transferred to water through passive heating coil. Heat absorbed by therminol is calculated by knowing the inlet and outlet temperatures at the header. Similarly heat gained by the water is calculated by knowing the inlet and outlet temperatures of water at the storage tank. The ratio of heat gained by the water to heat lost by therminol will give the heating efficiency.

Heat gained by the water, $Q_W = m_w C_{pw}(T_{wi} - T_{wi})$ ----- (1)

Heat lost by therminol, $Q_t = m_t C_{pt}(T_{ti} - T_{to})$ ----- (2)

Heating efficiency, $\eta = \frac{Q_w}{Q_t}$ ----- (3)

An uncertain analysis was carried out on the reduced data based on the propagation of error method described by Kline and McClintock [21, 22]. Table 2 presents the accuracy of various measuring devices used in the experiment. Uncertainty in heat efficiency is calculated for various test runs. For a moderate flow rate and the solar irradiance, the uncertainty in the efficiency is found to be around 5%. The uncertainty is greatly influenced by direct irradiance.

TABLE 2
Uncertainties of Measurement Devices

Parameter	Uncertainties
Mass flow rate	$\pm$0.25%
Temperature difference (Thermocouple)	$\pm$0.1 K
Direct irradiance (Pyranometer)	$\pm$5%

V. RESULTS AND DISCUSSION

The study is carried out from September2012 to February2013. The experiment is conducted from 0700 hours to 0900 hours in the morning and 0400 hours to 0600 hours in the evening. In the morning hours the solar radiation varied between 200 W/m^2 and 600 W/m^2. In the evening hours the radiation range is between 50 W/m^2 and 400 W/m^2. The optimum flow rate of heat transfer fluid for heat pipe based solar collector was studied by

Azad [7]. Based on that study, the flow rate of water and therminol are chosen as 0.005 and 0.008 kg/s respectively in the morning hours. In the evening hours the solar radiation gradually gets decreased and because of that there occurred a small drop in mass flow rate. The flow rates of water and therminol were found to be 0.004 and 0.005 kg/s respectively. Experiments were conducted on therminol based system and water based system simultaneously.RO treated water is used in the water based system to avoid scale deposits. Figure 4 gives the variation of heating efficiency of both therminol based and water based system.

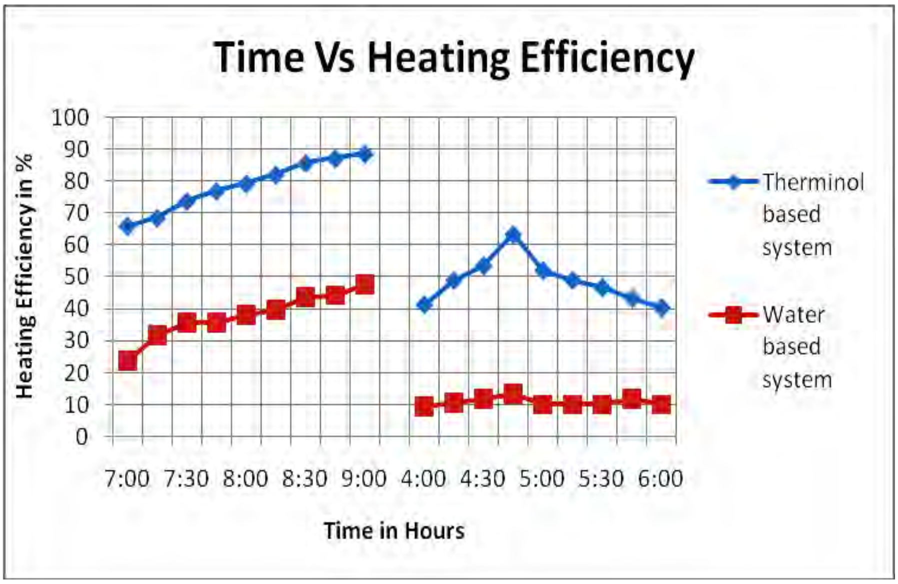

Figure 4 Variation of heating efficiency of therminol based and water based systems

The heating efficiency of therminol based system is 40% higher in the morning hours and 25% higher in the evening hours than that of water based system. Figure 5 shows the average variation of solar radiation from September2012 to February2013 during the experimentation hours. The temperature characteristics obtained for therminol based system and water based system are shown in Figure 6 and Figure 7 respectively. The rise in temperatures is better during morning hours in comparison to evening hours. The instant hot water is produced at a temperature of around 40°C in the evening hours in therminol based system while in water based system the hot water temperature is around 32°C. Figure 8 shows the outlet temperature variations in both the systems against different time periods.

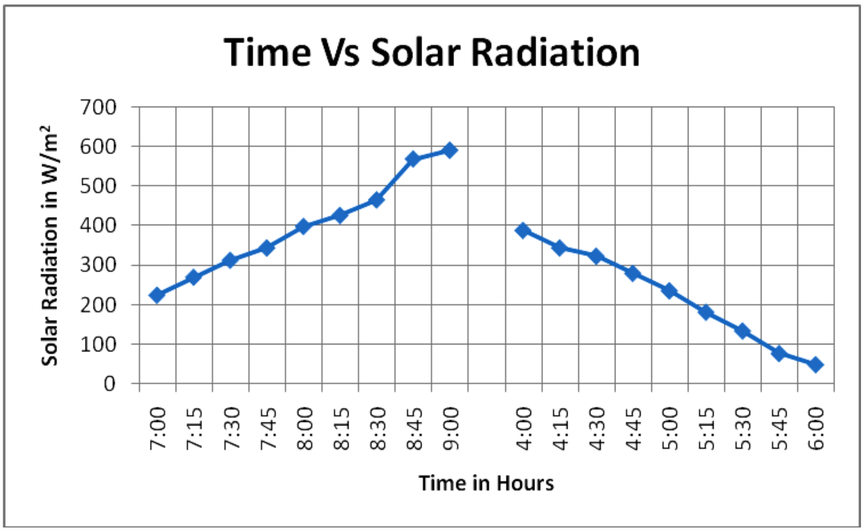

Figure 5 Average variation of solar radiation during experimentation hours

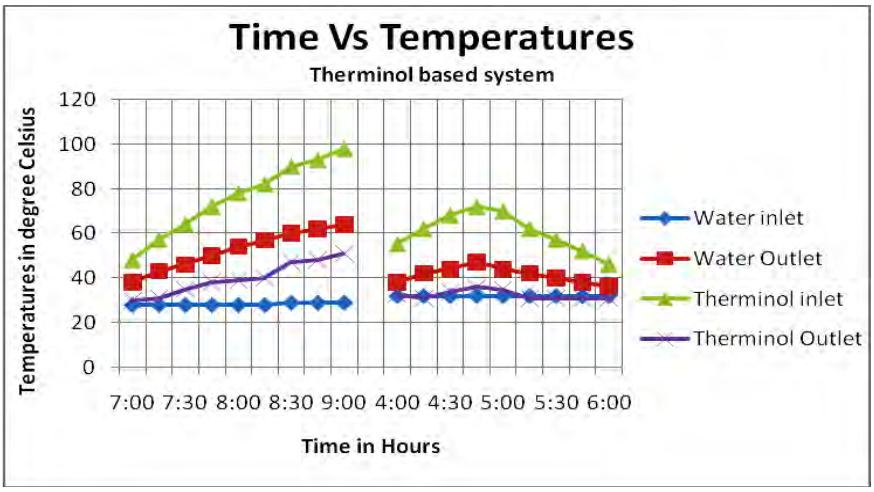

Figure 6 Temperature characteristics obtained from the experiments on therminol based system

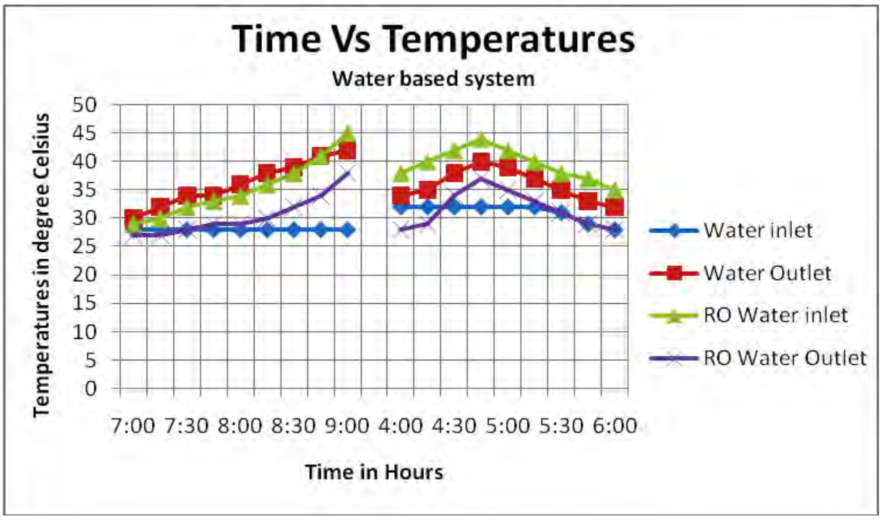

Figure 7 Temperature characteristics obtained from the experiments on water based system

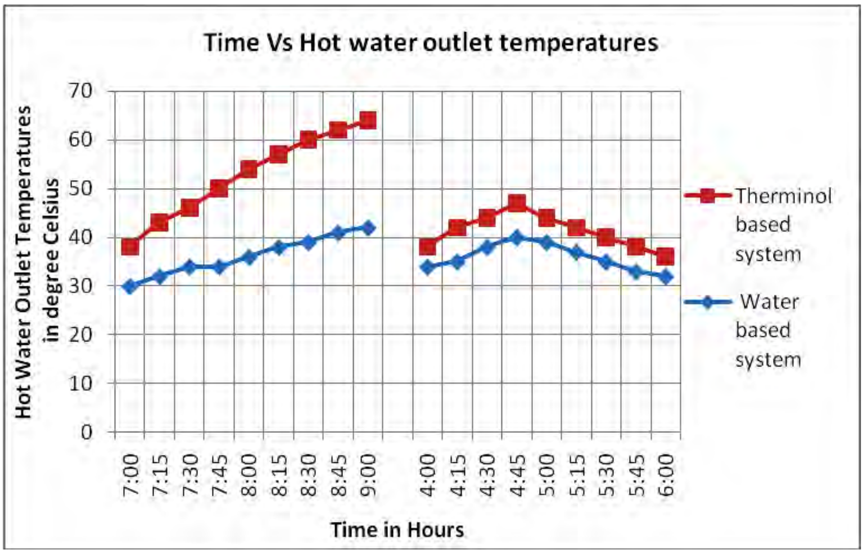

Figure 8 Variation of hot water outlet temperatures at different time periods

The heating efficiency curves obtained from the experiment can be modeled as quadratic function for the morning hours and evening hours for the two different systems. The expressions are as follows.

For therminol based system, heating efficiency in morning hours is given by

$$\eta = -14.51 + 279.63t - 29.78t^2 \qquad \text{----- (4)}$$

For therminol based system, heating efficiency in evening hours is given by

$$\eta = 65.09 - 77.79t + 12.30t^2 \qquad \text{----- (5)}$$

For water based system, heating efficiency in morning hours is given by

$$\eta = -43.48 + 243.73t - 25.95t^2 \qquad \text{----- (6)}$$

For water based system, heating efficiency in evening hours is given by

$$\eta = 11.22 - 1.33t + 0.18t^2 \qquad \text{----- (7)}$$

For solar radiation varying from 50 to 500 W/m^2, instant hot water at a temperature of 60°C can be produced with therminol based system. In the same limit of solar radiation, the temperature of instant hot water is around 40°C in water based system.

VI. CONCLUSIONS

The evacuated tube collector coupled with parabolic trough with therminol D-12 as heat transfer fluid has been studied for instant hot water generation within short period of time. The problems associated with present day evacuated tube solar collector can be rectified with the newly developed system. In the presence of low solar radiation, the behavior of therminol based system is 2 times better than water based system. The commercial evacuated tube collectors without parabolic trough and with water as heat transfer fluid cannot produce instant hot water at 60°C in the presence of low solar radiation within short period of time. The cost benefit studies and degradation characteristics of therminol D-12 oil are being studied for further improvement of the system.

NOTATIONS USED

C_{pt} Specific heat of therminol in kJ/kg K
C_{pw} Specific heat of water in kJ/kg K
m_t Mass flow rate of therminol in kg/s
m_w Mass flow rate of water in kg/s
T_{ti} Inlet temperature of therminol in °C
T_{to} Outlet temperature of therminol in °C
T_{wi} Inlet temperature of water in °C
T_{wo} Outlet temperature of water in °C
t Time in hours
Q_w Heat gained by the water in W
Q_t Heat lost by therminol in W
η Heating efficiency in %

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