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Performance study on evacuated tube solar collector using therminol D-12 as heat transfer fluid coupled with parabolic trough

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ABSTRACT

Fossil fuels and electrical energy are widely used for instant hot water generation in rural and urban areas. Also, conventional solar water heaters do not support instant hot water generation because of various problems. A new system with evacuated tube collector using synthetic oil as heat transfer fluid coupled with parabolic trough is developed and studied experimentally for instant hot water generation in the presence of low solar irradiance. Among the different grades of therminol, therminol D-12 is chosen for the study because of its thermal stability. Parabolic trough is coupled to evacuated tube to enhance the flow as well as heating characteristics of therminol. Heating efficiency and temperature characteristics are determined for the newly developed system under low solar irradiance conditions. Instant hot water can be produced by the new system at a temperature of 60 °C in the presence of low solar radiation. This newly developed system has the ability to check the fossil fuel consumption and electrical energy consumption for instant hot water generation in household applications. The stability of the heat transfer fluid is also ensured by repeated experiments.

1. 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 modeling. Fluid-in-glass evacuated tube cannot withstand high pressures and hence it is suitable for applications where few meters 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]. Malika Ouagued et al. [17] studied the properties of different thermal oils and determined the thermal performance of the heat transfer fluids under Algerian climate. Parabolic trough collector and thermal oil are used in their project for high temperature

Abbreviations: HTF, heat transfer fluid; PT, parabolic trough.

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Nomenclature

C_{pt}	specific heat of therminol in kJ/kg K	T_{wi}	inlet temperature of water in °C
C_{pw}	specific heat of water in kJ/kg K	T_{wo}	outlet temperature of water in °C
m_t	mass flow rate of therminol in kg/s	t	time in hours
m_w	mass flow rate of water in kg/s	Q_w	rate of heat gained by the water in kJ/s
T_{ti}	inlet temperature of therminol in °C	Q_t	rate of heat lost by therminol in kJ/s
T_{to}	outlet temperature of therminol in °C	η	heating efficiency in %

applications. A temperature controlled parabolic trough was designed and analyzed by Ilhan Ceylan and Alper Ergun [18]. Water was used as heat transfer fluid and the highest energy efficiency obtained was around 61%. 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. Li and Wang [19] investigated the heating of evacuated tube by solar trough concentrating system. Heating of water and nitrogen by parabolic trough concentrator was performed and the problems associated with the heating processes were discussed. Therminol D-12 oil is chosen as a heat transfer fluid in the present study because of its low viscosity and stability in the operating temperature range. 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. [20]. Parabolic troughs are used in medium and high temperature applications. In this paper, it is proved that parabolic trough can be used in low temperature applications. In the presence of low solar radiation, the existing systems are not reliable for instant hot water generation. The other benefits of the new system include reduction in fossil fuel consumption in suburbans and cooking gas and electricity consumption in urban areas which are used for instant hot water generation. The space requirement for the new system is also much smaller as compared to conventional solar water heaters.

1.1. 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. [21] 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 Fig. 1.

Therminol D-12 which has flash point of 62 °C (Pensky-Martens) and fire point of 79 °C (ASTM D-92) 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 D-12 with that of water is shown in Table 1.

2. Experimental set-up

The experimental set-up which is shown in Fig. 2 consists of a parabolic trough, an evacuated tube solar collector and a heat exchanger type storage tank. A standard evacuated tube collector of length 1500 mm and diameter 47 mm 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 Fig. 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. The parabolic trough is fabricated by stainless steel sheet with an aperture area of 1.2 × 0.6 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. 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. For testing the solar collector as per the standards, the wind velocity should be less than 0.2 m/s. For comparing the performance of the same set-up with water as heat transfer fluid, experiment is carried out simultaneously. The schematic sketch of experimental test rig is shown in Fig. 4.

For countries with tropical climatic conditions, the instant hot water requirement is more in the morning hours particularly from the month of September to February. The beam radiation varies between 300 and 500 W/m^2 during the period. As the aim of the present work is to produce instant hot water during low solar radiation, the experiment is conducted from 0600 h to 0900 h in the morning. The shadow effect caused by the tubes on parabolic trough is 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.

3. Performance calculations

The thermal efficiency of the system is defined as the 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. [22]. The formula for calculating parabolic trough collector efficiency is reported by Li et al. [23]. 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. For passive heating applications, heating efficiency is defined as the ratio of heat gained by secondary fluid to heat lost by primary fluid. Heat absorbed by therminol (primary fluid) is calculated by knowing the inlet and outlet temperatures at the header. Similarly heat gained by the water (secondary fluid) 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.

Rate of heat gained by water, $Q_w = m_w C_{pw}(T_{wo} - T_{wi})$ (1)

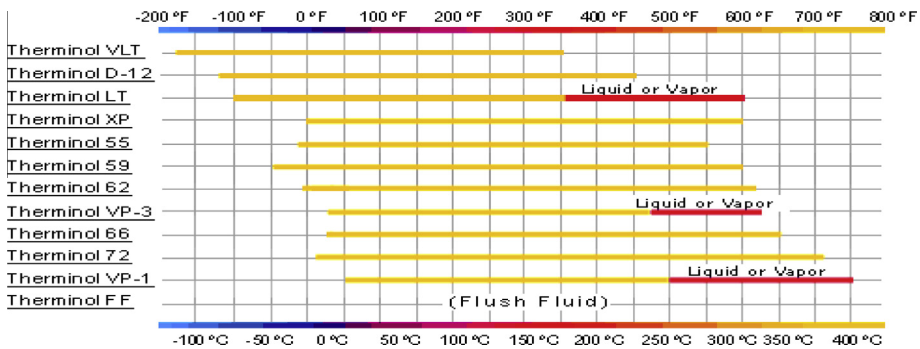

Fig. 1. Therminol grades and operating temperature limits. (*Source*: http://www.therminol.com)

Table 1
Comparison of properties of therminol D-12 and Water.

Properties	Therminol-D12	Water
Density at 20 °C	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	0.801 centi Stoke @ 30 °C
	0.66 centi Stoke @ 100 °C	0.294 centi Stoke @ 100 °C

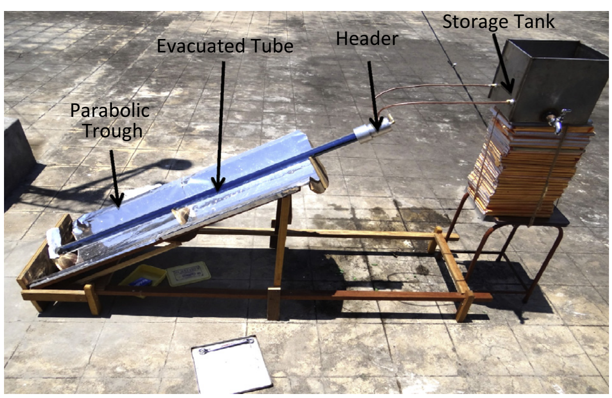

Fig. 2. Photograph of experimental set-up with parabolic trough, evacuated tube, header and storage tank.

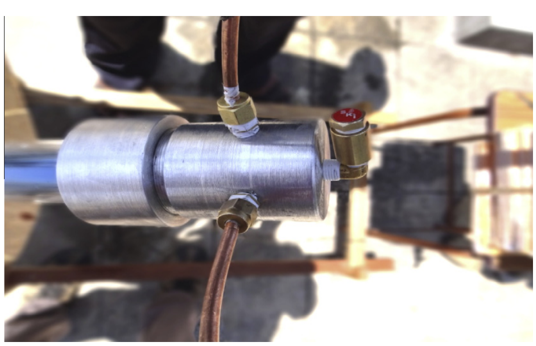

Fig. 3. Photograph of header with inlet and outlet ports.

$$\text{Rate of heat lost by therminol, } Q_t = m_t C_{pt}(T_{ti} - T_{to}) \quad (2)$$

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

An uncertainty analysis was carried out on the reduced data based on the propagation of error method described by Kline and McClintock [24,25]. Table 2 presents the accuracy of various measuring devices used in the experiment.

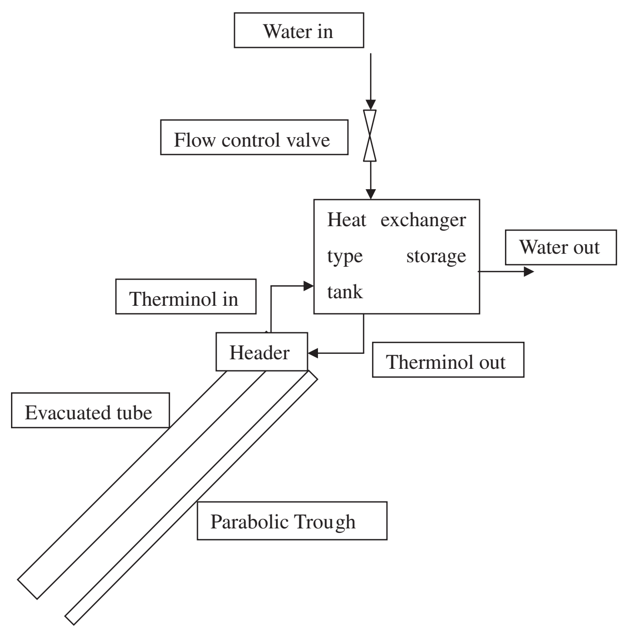

Fig. 4. Schematic diagram of experimental set-up.

Table 2
Uncertainties of measurement devices.

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

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. For studying the transient behavior of the system, time constant is determined based on the guidelines given in ASHRAE 1977 standards. The calculations on heat loss coefficient and optical efficiency are not taken into account because the experiment is carried out for three hours only and the incident solar radiation is low. Also, the wind speed during the experimentation period is less than 0.5 m/s.

4. Results and discussion

The study is carried out from September 2012 to February 2013. The experiment is conducted from 0600 h to 0900 h in the morning during which the solar radiation varied between 200 W/m^2 and 600 W/m^2. The flow rate of water and therminol are chosen as 0.05 and 0.08 kg/s respectively. Experiments were conducted with and without parabolic trough simultaneously.

Fig. 5 gives the variation of heating efficiency of the system with parabolic trough at specified time intervals. The heating efficiency reached 80% at 0630 h. There are two outlets for therminol, one at the evacuated tube and the other at the storage tank. The outlet temperature of therminol at evacuated tube is 90 °C at 0900 h. Fig. 6 shows the variation of storage tank outlet temperatures of therminol and water. Instant hot water is produced at 40 °C at 0645 h in the presence of 240 W/m^2 solar radiation.

The temperature of water reached 68 °C maximum at 540 W/m^2. Fig. 7 depicts the variation of useful heat gain and incident solar radiation for the experimentation period. When the incident radiation is above 390 W/m^2, the useful heat gain is prominent.

The variation of water inlet temperature, water outlet temperature and ambient temperature during experimentation period is depicted in Fig. 8.

Efficiency of the system is expressed in terms of temperature difference and incident beam radiation based on Fig. 9.

$$\eta = 8.6025\left(\frac{T_b - T_a}{I}\right) + 0.6552 \tag{4}$$

The R^2 (0.81) and Y-intercept (0.6552) obtained from the instantaneous efficiency curve are acceptable with the previous works. Y-intercept value is an indicator of optical efficiency of the system. The comparison of Y-intercept value with previous researchers is given in Table 3.

The time constant curve is shown in Fig. 10. The time constant value obtained through transient heat conduction relation is 60 s and it is close to the value obtained by other researchers. Similar experiment is conducted on evacuated tube with therminol D-12 as heat transfer fluid in the absence of parabolic trough. This study is carried out to find the effect of parabolic trough in the system. Fig. 11 shows the comparison of outlet temperatures of therminol and water with and without parabolic trough.

The maximum temperature attained in case of system without parabolic trough is 40 °C at 540 W/m^2 which is less by 28 °C in comparison to the system with parabolic trough. Fig. 12 shows the comparison of useful heat gain in the systems with and without parabolic trough. Useful heat gain in case of parabolic trough coupled system is far better than that of the system without parabolic trough.

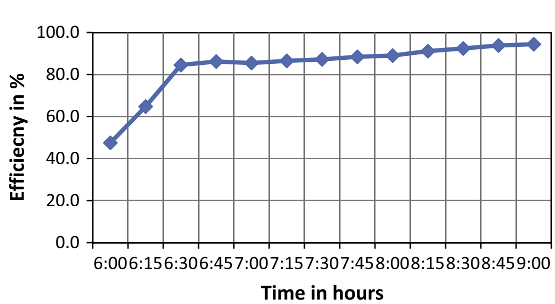

Fig. 5. Variation of heating efficiency of the system with parabolic trough at specified time intervals.

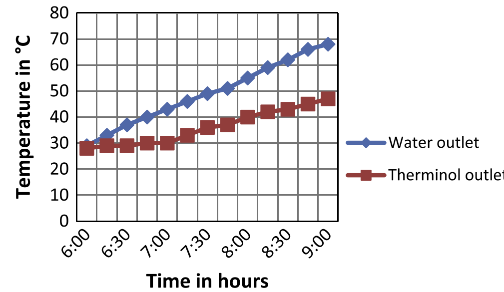

Fig. 6. Variation of storage tank outlet temperatures of therminol and water at specified time intervals.

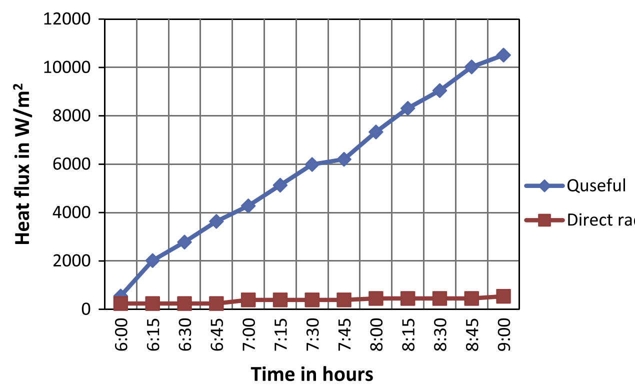

Fig. 7. Variation of useful heat gain and incident solar radiation for the experimentation period.

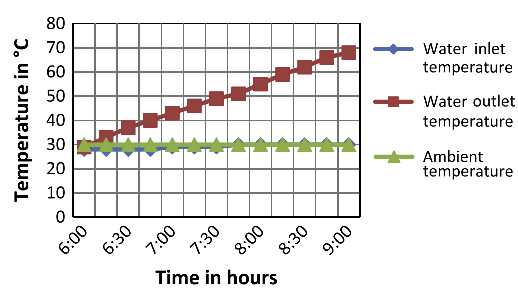

Fig. 8. Variation of water inlet temperature, water outlet temperature and ambient temperature during experimentation period.

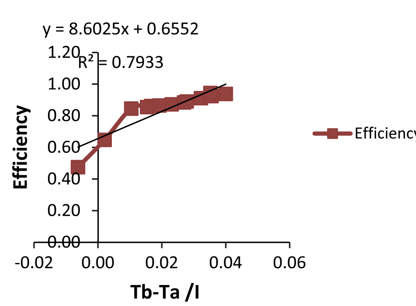

Fig. 9. Instantaneous efficiency curve.

From Figs. 13 and 14, it is clear that efficiency of the system with parabolic trough is nearly 30% greater than that of the system without parabolic trough.

The variation in properties of therminol D-12 after continuous usage is also studied. The flash point and fire point of the oil dropped by 1 °C after 100 cycles of operation. The variation of

Table 3
Comparison of *Y*-intercept values with previous researchers.

Y-intercept value	References
0.642	Kalogirou et al. [26]
0.638	Kalogirou [27]
0.6905	Valan Arasu and Sornakumar [28]
0.622	Senthilkumar et al. [29]
0.6552	Present work

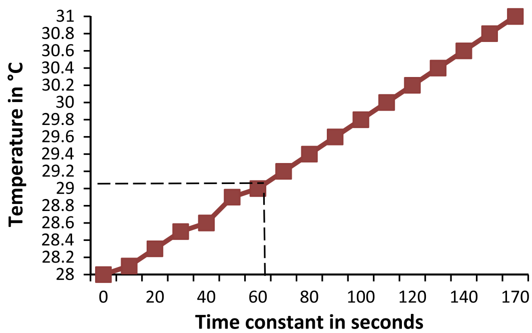

Fig. 10. Time constant curve.

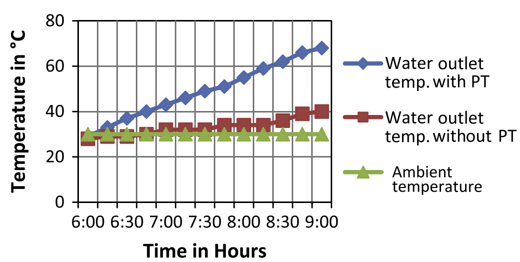

Fig. 11. Comparison of outlet temperatures of therminol and water with and without parabolic trough.

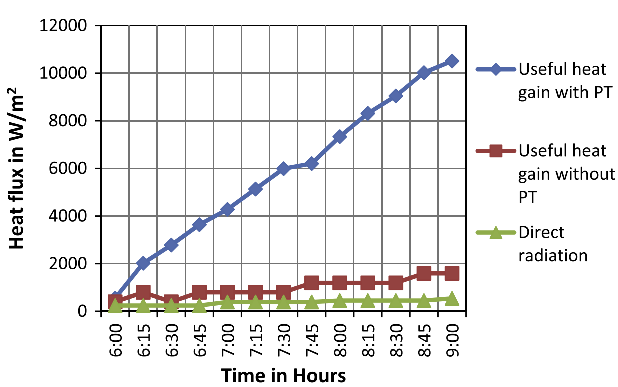

Fig. 12. Comparison of useful heat gain in the systems with and without parabolic trough.

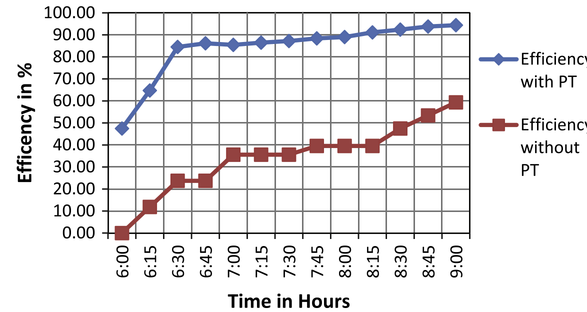

Fig. 13. Comparison of heating efficiency of the systems with and without parabolic trough.

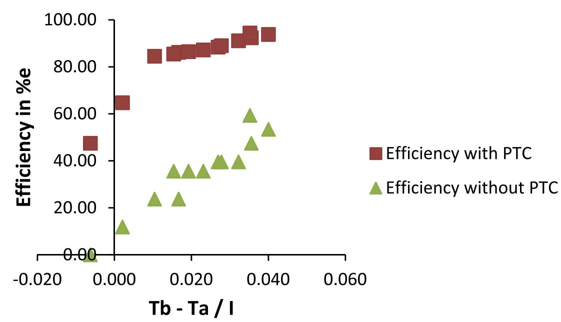

Fig. 14. Comparison of instantaneous efficiency of the systems with and without parabolic trough.

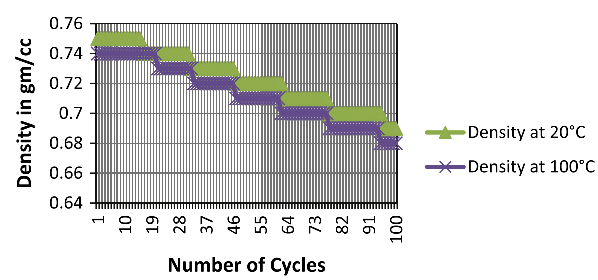

Fig. 15. Variation of density of therminol during 100 cycles of operation.

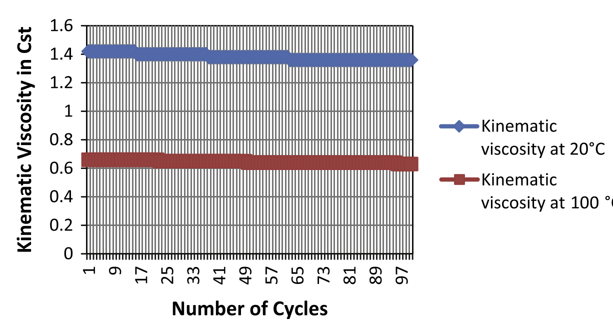

Fig. 16. Variation of kinematic viscosity of therminol during 100 cycles of operation.

density and kinematic viscosity are measured and plotted in Figs. 15 and 16 respectively for 100 cycles of operation.

There is no significant variation in the above mentioned properties. The boiling point of therminol D-12 is 192 °C and it will not change to vapor state easily. However, for ensuring the safety of the system, a safety valve is provided at the header region to withstand excess pressure if produced inside the evacuated tube. The experiment is conducted regularly for six months period and no accidents had happened. Therminol D-12 is an FDA recognized fluid and has excellent industrial hygiene properties. This oil meets the requirements established by the FDA at CFR 172.882, 172.884, 178.3530 and 178.3650.

5. 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 under low solar radiation. Evacuated tube using therminol D-12 as heat transfer fluid coupled to parabolic trough can produce instant hot water at temperatures between 40 °C and 68 °C under low solar radiation. Therminol D-12 can be used as a heat transfer fluid in solar collectors where scale formation is predominant due to greater hardness of water. Use of parabolic trough along with evacuated tube can increase the heating efficiency by 30% in the instant hot water generation process. The thermal and flow properties of therminol D-12 remain stable even after 100 cycles of operation.

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