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Performance Analysis of Flat Plate and Evacuated Tube Collectors

Abdi Chimdo Anchala, Chandraprabu Venkatachalam, Addisu Bekele , Mohanram Parthiban

Abstract: ***This study gives a thermal analysis on the effect of operating parameters on the performance of solar water heating systems with two distinct collector configurations; flat plate and heat pipe evacuated tube collectors. The thermal analysis of these two systems was conducted based on the account of variation in weather conditions of Adama and volume flow rate, using T*SOL® Simulation software, to study the impact of these operating conditions on the system efficiency, system solar fraction, storage tank outlet temperature, collector outlet temperature, energy accumulated and collected in the tank and collector. This is done to compare the performance of these two systems with each other, based on thermal analysis in order to provide the necessary information required to select the most appropriate solar collector and its operating conditions. The results showed that for a fluid circulating at 120 l/h, the highest monthly solar fraction of FPC and ETC systems were 80% and 64.6%, respectively, around November with a total solar irradiation of 191 kWh/month. For both systems, the hourly tank outlet temperature peaked in November to 87 °C and 71.2 °C for ETC and FPC, respectively. For a typical day in April, the maximum tank outlet temperature becomes 74 and 62.5 °C. Regarding the flow rate, simulation of the systems is done for three flow rates (80, 120 and 160 l/h). The results also showed that for a typical day in April, the hourly maximum tank inlet-outlet temperature difference was obtained for both ETC and FPC at 12:00 PM at a flow rate of 160 l/h, where the corresponding maximum tank outlet temperature becomes 74 and 62.5 °C. At this volume flow rate, a solar water heating system efficiency of 59% and 50%, and also a system solar fraction of 82% and 68.1% could be achieved for a SWH system employing ETC and FPC, respectively. Overall, ETC systems proved to be a more efficient system to satisfy the need of hot water.***

Keywords: ***Solar energy, Solar water heating system, thermal analysis, flat plate collector, evacuated tube collector***

I. INTRODUCTION

Energy plays a pivotal role in our society because of new the life trends which are accompanied with high energy consumption.

In a modern society we live in, demand for electric energy is on the rise throughout the world.

The tendency of global demand reveals that the emerging economies will begin to require more and more electricity, given their exponential growth.

Due to this increasing energy demand, our society has been on the lookout to find different kind's energy sources and the best option is discovered to be using renewable energy. One form of renewable energy is solar energy [1].

Solar energy is heat and radiant light (energy) from the sun. Solar energy technologies produces marketable energy by converting this natural phenomena (sun radiation), into either electrical energy or thermal energy by using solar collectors [2]. The development of solar energy requires accurate estimation of the available solar energy resources and suitable sites for solar collector installations. The generation and distribution of solar energy is highly dependent on the geographical location and topography. Besides providing a more sustainable hot water, the dimensions of a collector has an effect of little to none on the performance of the system, so the exergy analysis is preferable to compare the thermal performance of collectors with different configurations [3]. Ethiopia has abundant solar energy resources. The national daily average irradiance is estimated to be 5.2 kWh/m^2/day with seasonal variations that range between the minimum of 4.5 kWh/m^2/day in July to a maximum of 5.6 kWh/m^2/day in February and March [4].

Solar Water Heating (SWH) systems installed in Ethiopia are mostly simple and modular collectors with separate water tanks. An estimated 80% of total installed capacity of SWHs is within Addis Ababa [4].

The proper design of SWH systems is important to assure good performance. There are many studies in the literature that address the design method of these systems. These design methods can be broadly classified into two categories, namely, correlation-based methods and simulation-based methods [5]. On the other hand, a number of simulation-based methods such as TRNSYS, T*SOL and SOLCHIPS have been applied for the design of SWH systems and are also available on the market as user-friendly software tools. Researchers and designers can numerically evaluate the effects of design variables on long-term energy performance by conducting a series of simulations. These design variables could include the collector area, number of the collectors, storage tank volume, auxiliary heater capacity, and number of the auxiliary heaters. However, even one of these design variables could cause a variation in the SWH system's performance. Therefore, the number of simulations increases exponentially according to the increase in the number of design variables and parameters. Moreover, these methods also require the involvement of experts and significant computation time [6].

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* Correspondence Author
Abdi Chimdo Anchala*, Lecturer, Department of Mechanical Engineering, Ambo University, Ambo, Ethiopia. Email: abdichimdo@gmail.com
*** Chandraprabu Venkatachalam**, Assistant Professor, Department of Mechanical Engineering, Adama Science and Technology University, Adama, Ethiopia. Email: vchandraprabu@gmail.com
Addisu Bekele, Assistant Professor, Department of Mechanical Engineering, Adama Science and Technology University, Adama, Ethiopia. Email: addisu2009@gmail.com.
Mohanram Parthiban, Lecturer, Department of Mechanical Engineering, Adama Science and Technology University, Adama, Ethiopia. Email: lillymohan@yahoo.com.

II. LITERATURE REVIEW

A. Overview of Solar Water Heating Systems

The idea of using solar energy collectors to harness the sun’s power is recorded from the prehistoric times. The manufacture of solar water heaters (SWH) began in the early 1960’s. Since then, the industry of SWH’s have expanded very quickly in many countries of the world. The greatest advantage of solar energy as compared with other forms of energy is that it is clean and can be supplied without any environmental pollution [7].

B. Solar Thermal Collectors

Solar collectors are devices that are used to harness the energy from the sun, converting the incoming solar radiation into useful heat energy. Being the key element in solar energy utilization systems, solar energy collectors act as heat exchangers that converts the solar radiation energy into internal energy of the transport medium. The solar energy will be collected by absorbing the incoming solar radiation and converting it into heat, and transferring this heat to a fluid. Then, this heat energy will be transferred from the fluid to the heat application processes or the storage tank [8].

Stationary solar collectors are permanently fixed in position and do not track the sun. Three types of collectors fall in this category are Flat plate collectors (FPC), Stationary compound parabolic collectors (CPC) and Evacuated tube collectors (ETC) [1].

The energy generated by a solar collector is dependent on the angle at which it is tilted and the orientation of the solar collector. For maximum energy gain, solar panels should be inclined at optimal tilt angle and seasonal adjustment of the panel may lead to considerable gain in energy obtained from solar energy. The optimum North – South tilt angle and East- West orientation angle is different for each months of the season and shows variation in the direction of sun with time of day and month of the season. The collected solar energy will be greater if we choose the optimum panel tilt for the season [9].

B.i. Flat plate collector

Flat plate collectors (FPCs) are primarily composed of a glass cover, absorber plate and insulation material. The glass cover is used to trap the hot air by reducing the radiation and convection losses to the surrounding, the absorber plate has tubes filled with the working fluid whereas the insulation material is used to reduce conduction losses [10]. A typical flat-plate solar collector is shown in Fig. 1.

Addisu et al. [11] investigated the potential use of solar energy for large-scale water heating systems on four selected sites; Addis Ababa tannery, Dire tannery, Ethiopian tannery and Jimma hospital, Ethiopia. The transient analysis was performed for a 2 m^2 flat plate collector and the system gave a corresponding solar contribution to the heating load and a maximum solar fraction of 1 and 80.9% for Addis Ababa tannery; 0.981 and 76.2% for Dire tannery; 0.91 and 81.6% for Ethiopian tannery; and 0.975 and 81.8% for Jimma hospital, thus proving solar energy can be used for large-scale water heating systems in Ethiopia.

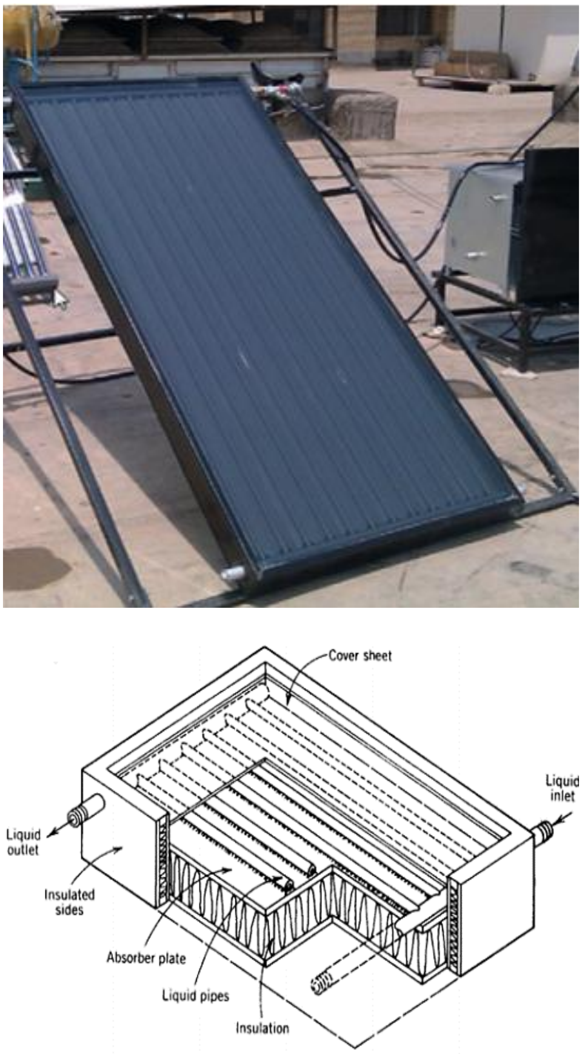

Figure 1. Pictorial view and sectional view of flat plate collector [22]

By increasing the mass flow rate of the working fluids we can increases the efficiency of the flat plate collector. Water gives a lower efficiency at lower flow rates but for a flow rate of 0.016 kg/s and above, since the pumping power adversely affects the thermal efficiency of the collector, at the turbulent flow conditions water becomes more efficient HTF [12].

The investigations on the performance of FPC were done for two different two climatic conditions with TRNSYS software. In order to get suitable outlet temperature (70 to 90 °C) they used three collectors which are connected in series. Based on the study the thermal efficiency is increased with increasing the inlet temperature. So the first collector has more useful energy gain (3775 kJ/hr) than the second one (3300 kJ/hr) also, the useful energy gain is more than from the second one is more than the third one (2825 kJ/hr) [13].

Lacour et al. [14] carried out the year round performance analysis of two commonly of two commonly installed forced circulation SWH systems in temperate climates has been carried out using trial installations.

Results obtained show that for an annual total in-plane solar insolation of 1087 kWh/m^2, a total of 1984 kWh of heat energy were collected by the 4 m^2 FPC system. Over the year, a unit area of the FPC generated 496 kWh/m^2 of heat. For 3149.7 kWh of auxiliary energy supplied to the FPC system, its annual solar fraction was 38.6%. The annual average collector efficiency was 46.1 and 60.7% while the system efficiency was 37.9%.

B.ii. Heat pipe evacuated tube collector

Heat pipe evacuated tube collector (ETC) contain two glass tubes made of borosilicate where the inner and outer glass tubes are separated by vacuum space. The vacuum plays the role of an insulator to block the short wave radiation from escaping and this has proven to be the best methods to trap radiation. It is also used to direct the radiant energy incident inside the tube without a huge heat loss. These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in Fig. 2 [15].

Evacuated tube collector is preferably used for high temperature applications such as desalination of sea water, air conditioning, refrigeration, and industrial heating processes since their performance is better than that of Flat Plate Collectors [16].

Xianhua et al. [17] stated that, higher thermal efficiencies can be achieved for the evacuated tube solar collectors by the reducing the inlet fluid temperature. For temperatures below zero, the thermal efficiencies increase as the reduced temperature decreases, and the growth rate of the thermal efficiency will decreases slowly.

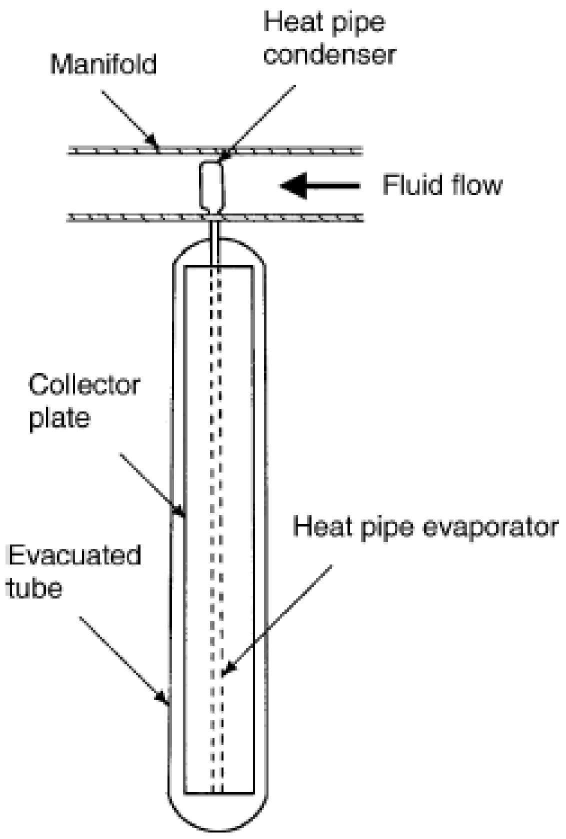

Figure 2. Pictorial and sectional view of heat pipe evacuated tube collector [8].

The heat collecting efficiency of evacuated tube solar collector is conducted by the simulation method. The results show that the annual average heat efficiency of the evacuated tube solar water heating system is 42.9%. The heat efficiency of ETC was the largest in August, and the lowest in December, which goes to show that the air (ambient) temperature has great influence on the heat collecting efficiency of the collector [18].

After conducting an investigation on 2m^2 concrete absorber plate solar water heater, Ajinkya [19] stated that, during months of September, January and April average water temperature of 150 *l* of water collected per day is found to be 62, 59 and 69 °C respectively at a water flow rate of 30 *l*/h. Thus, with this capacity of the evacuated tube solar water heater, it is possible to fulfil the demand of hot water for various purposes in most weather conditions mostly for normal weather days and partially, for cloudy days.

III. SIMULATION SETUP

A. Simulation software

In this study, the T*SOL® Pro 5.5 (R6) analysis tool is used for analysing the solar water heating system. T*SOL® is a dynamic software programme used to simulate and optimise solar thermal systems such as hot water systems and space heating applications. This is preferred to other analysis tools because it has an integrated MeteoSyn tool which allows users to create climate data for locations outside of the included data base.

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B. Weather data

For this study, the solar radiation, ambient temperature and wind speed of Adama, Ethiopia (8.33^0 N and 39.17^0 E) was selected from the MeteoSyn tool database, and based on this data, the simulation analysis was done on each hour, day and months of a year.

C. DHW consumption profile

The DHW requirement and its distribution over a year are key values for simulating a solar system. The monthly average hot water consumption is roughly constant across a year. For this study. Adama's daily load pattern used for the load cycle simulations was adopted for detached house (Single-family dwelling), together with the simulation software's automated hot water draw off system to mimic domestic hot water use. An average household in Adama uses about 75 L of hot water per person per day and according to the Ethiopia Rural Socioeconomic Survey (ERSS) [20], Ethiopia's average household size is 5 persons. This means, for a family of five, the total daily hot water consumption will be 375 *l*. Fig. 3 shows the profile of the daily domestic hot water demand.

D. Description of the SWH systems

An indirect active system was selected as the basis for the design of the systems. The main components of the SWH system includes solar thermal collector, electric pump and storage tank. A schematic diagram of the examined water heating systems is shown in Fig. 4.

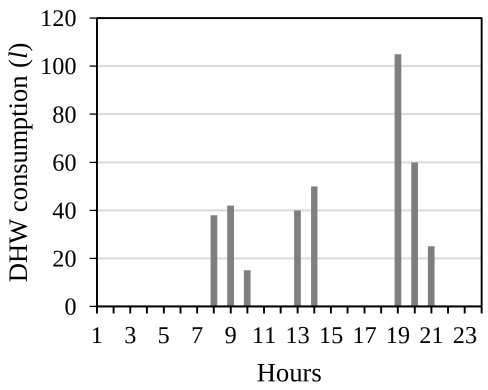
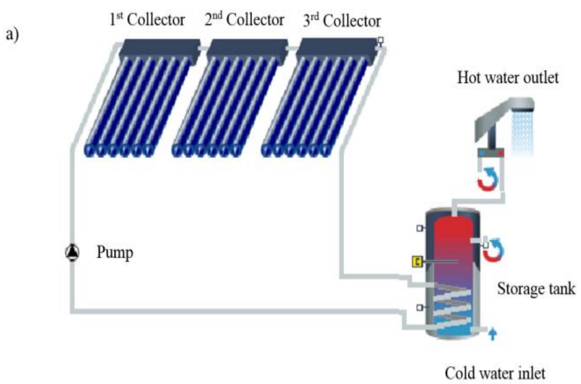


Figure 3. DHW consumption at different times of a particular day



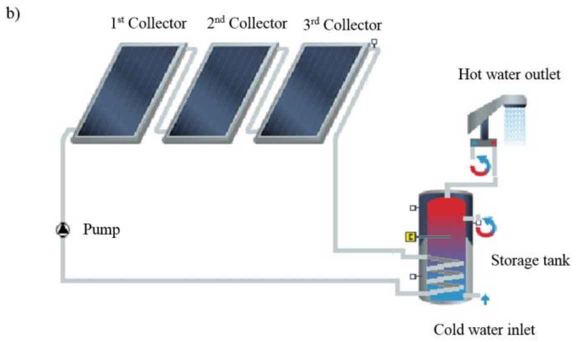


Figure 4. Schematic diagram of a) ETC and b) FPC SWH systems

D.i. Thermal collector

T*SOL® provides up to date database of many certified solar collectors which are tested according to the Solar Collector Certification Program (SRCC) and certified by independent institutes. Out of those collectors, the type KSC-AE/200/S and OPC 15 are selected for the simulation representing the flat plate collector and heat pipe evacuated tube collector, respectively. In order to get suitable water outlet temperature (60 °C), the SWH system is modelled with three collectors which are connected in series. Here, the outlet temperature of the second and subsequent collectors will be more and not the same as the first, because its inlet temperature is the outlet temperature of the first, and the water collects more and more energy along its way.
The rate of thermal energy of the tubular collector available will be carried away by the fluid flowing through the tube under steady-state conditions. This can be calculated using the energy balance on the fluid volume as follows:

$$Q_u = \dot{m}\, C_p\left(T_{fo} - T_{fi}\right) \qquad (1)$$

The collector efficiency is defined as the ratio of the actual useful energy gain over a specific period of time to the incident solar energy over the same period, and it can be computed by the following equations:

$$\eta_{collector} = \frac{Q_u}{A_p\, I} \qquad (2)$$

$$\eta_{1^{st}\ collector} = \frac{\dot{m}\, C_p(T_2 - T_{fi})}{I\, A_{C1}} \qquad (3)$$

$$\eta_{2^{nd}\ collector} = \frac{\dot{m}\, C_p(T_3 - T_2)}{I\, A_{C2}} \qquad (4)$$

$$\eta_{3^{rd}\ collector} = \frac{\dot{m}\, C_p(T_{fo} - T_3)}{I\, A_{C3}} \qquad (5)$$

$$\eta_{overall\ collectors} = \frac{\dot{m}\, C_p(T_{fo} - T_{fi})}{I\, A_C} \qquad (6)$$

The energy absorbed by the collector and output to the collector loop with heating losses is calculated as follows:

$$P = I_{dir}\, \eta_o\, f_{IAM} + f_{IAM\,d}\ I_d\, \eta_o\, k_o(T_{Cm} - T_a)\, k_q(T_{Cm} - T_a)^2 \qquad (7)$$

with I_{dir} = Part of solar irradiation striking a tilted surface
I_d = Diffuse solar irradiation striking a tilted surface
T_{Cm} = Average temperature in the collector
T_a = Air temperature
f_{IAM} = Incident angle modifier

Table 1. Collector design parameters

Parameter	for ETC	for FPC
Type	OPC 15	KSC-AE/ 200/ S
Gross area of collector	2.13 m^2	1.94 m^2
Active area of collector	1.7 m^2	1.7 m^2
Length of collector	1.25 m	0.99 m
Width of collector	1.7 m	1.97 m
Number of collectors	3	3
Total active area of collector	5.1 m^2	5.1 m^2
Specific heat capacity of collector	12413 Ws/m^2 K	12059 Ws/m^2 K
Linear heat transfer coefficient	1.02 W/m^2 K	3.89 W/m^2 K
Height of collector	0.1 m	0.1 m
Surface azimuth angle	0°	0°
Collector inclination	20°	20°
Water inlet temperature	22.5 °C	22.5 °C

After deduction of optical losses, a part of the absorbed radiation is lost through heat transfer and radiation to the environment.

According to Adama city water supply corporation, the temperature of water supplied for Adama is between 21 °C and 24 °C, so average temperature of 22.5 °C was chosen as the water inlet temperature. Table 1 shows the characteristics of both collectors.

D.ii. Storage tank

As in all hot water systems, the storage tank's task is to balance peak demand and charging power in supplying hot water by compensating for time differences between solar energy supply and hot water requirements. Dual coil indirect hot water tank is applied for the storage tanks modelling of both systems from the T*SOL® component library. Assuming a fully mixed storage scenario the energy stored (Q_{st}) in the tank is expressed as:

$$Q_{st} = \dot{m}\, C_p\left(T_{tank\ out} - T_{fi}\right) \qquad (8)$$

The capacity of the storage tank should be large enough to cover for at least one day. For domestic hot water (DHW) storage, the tank should hold the average daily consumption (in *l*) for that residency. Using an average volume of 75 *l* per person per day, a five-person family will require a 375 *l* storage tank (5×75 l = 375 *l*), but to accommodate for guests or other unexpected personnel in the house, the tank is sized with a 20% allowance resulting a 450 *l* storage tank. The exterior of a storage tank would be insulated to retain heat and reduce losses. Specifications of the storage tank are given in Table 2.

Table 2. Hot water storage tank properties

Parameter	Value
Type	Dual coil indirect hot water tank
Volume	450 *l*
Height	1.35 m
Number of tanks	1
Insulation material	Mineral wool
Thickness of tank insulation	0.1m
Thermal conductivity of insulation	0.045 W/m K

The SWH system efficiency is defined as follows:

$$SWH\ system\ efficiency = \frac{Energy\ output\ from\ the\ SWH\ system}{Irradiation\ on\ to\ the\ collector} \qquad (9)$$

D.iii. Pump

A Standard single speed pump is used to circulate water from the storage tank in the solar collectors. The pump is switched on and off by the temperature difference between the solar tank and the standby tank. The pump's input energy fluctuates between 3 to 6 kWh depending on the fluid volume flowrate fluid inlet temperature and other changing parameters.

D.iv. Pipe and insulation

Pipes of the solar system must be fitted with thermal insulation so that thermal dissipation from the pipes does not deteriorate a total efficiency of the solar system. Heated water from the collector passes through a pipe connected to the hot water storage tank. From there, cold water move down the pipes into the solar collector where it was being heated, again. In addition to this, there will be a pipe where the hot water gets transferred from the storage tank in to the building. Some specifications of the pipe are given in Table 3.

E. Simulation parameters of examined SWH systems

Simulation of two SWH systems is performed for two collectors, ETC and FPC of the same size and system design parameters. Though, the temperature requirement for domestic applications is known to be at 49 °C, the desired DHW temperature is set to be 60 °C, because the hot water storage regulation, AS1056 [21]. The thermal analysis will be performed for two different operating variables which includes weather conditions and volume flow rate. The system operating parameters and their range of variation is given in Table 6.

Table 3. Specification of pipe and insulation

Parameter	Value
Pipe length (Inside the building)	7 m
Pipe length (Outside)	4 m
Diameter of pipe	0.02 m
Insulation type	Mineral wool
Insulation thickness	0.02 m
Thermal conductivity of insulation	0.045 W/m K

Table 4. Simulation parameters and their range of variation.

Variables	Simulation parameters
Solar radiation and ambient temperature (weather conditions)	Hourly, daily and monthly
Volume flow rate	80, 120 and 160 l/h

F. Methodology

The steps used to assess the Performance of the two collectors based on the performance in this paper were;

i. Determining the incident solar irradiation level on the plane of the collector
ii. Estimating the daily hot water heating requirement of the consumer
iii. Sizing the solar water heating (SWH) system
iv. Analyzing the system's thermal performance through annual simulation using the T*SOL® simulation program for solar thermal heating systems.
v. Record, organize and present the results in a meaningful way to discuss afterwards.

IV. RESULTS AND DISCUSSION

A. Validation of T*SOL simulation software

The validation focuses on the comparison between the simulation software and the experimental results for FPC. The experimental results has been done by Farzad and Emad [22], for flat plate collector. The experiments were conducted at the solar energy research center of Islamic Azad University, South Tehran branch in an open loop system equipped with electrical heater for the pre-heating of fluid, circulation pump for flow rate regulation, and flat plate collector as specified in Table 5. The output from the simulation software (T*SOL) has been run according to same configuration and parameters done in experimental work by them. Since they provided no information about the ambient air velocity used in their experimental facility, it is assumed as 3 m/s.

According to the results given in Table 6, there is a very good agreement between the experimental data [22], and the simulation predicted data of efficiency, absorber plate temperature and overall heat loss coefficient of the collector. In all the cases, the simulation software yields a result that is closely less or greater than the predicted values. The absolute errors of T*SOL for the collector efficiency, absorber plate temperature and overall heat loss coefficient for FPC system are 4.95%, 0.39% and 16.8%, respectively. This shows that, the simulation software (T*SOL) can be used to analyse any SWH problem since it gives almost same values as compared to the experimentation done in Farzad and Emad's research paper.

Table 5. Design condition for flat plate collector

Parameters	Value
Absorber area	1.6 m^2
Working fluid	Water
Optical efficiency	76%
Inlet water temperature	300 K
Emissivity of absorber plate	0.92
Thickness of the back insulation	50 mm
Thickness of absorber plate	0.75 mm
Thermal conductivity of the absorber plate	237 W/m K
Thermal conductivity of the insulation	0.04 W/m K
Inner diameter of pipes	13 mm
Collector tilt	40°
Adhesive resistance	Negligible
Thermal conductivity of water	0.608 W/m K
Specific heat capacity of water	4180 J/kg K
Dynamic viscosity of water	0.0004 kg/m s
Thermal conductivity of insulator	0.045 W/m K
Thermal conductivity of absorber plate	384 W/m K
Mass flow rate	0.04 kg/s

Table 6. The comparison between the simulation and experimental results

Output parameters	T*SOL	Experiment [22]	Difference
Collector efficiency (%)	48	50.5	-4.95%
Absorber plate temperature (K)	306.3	307.5	-0.39%
Overall heat loss coefficient (W/m^2 K)	3.4	2.91	+16.8%

B.Comparative analysis on effects of operating parameters on the SWHs

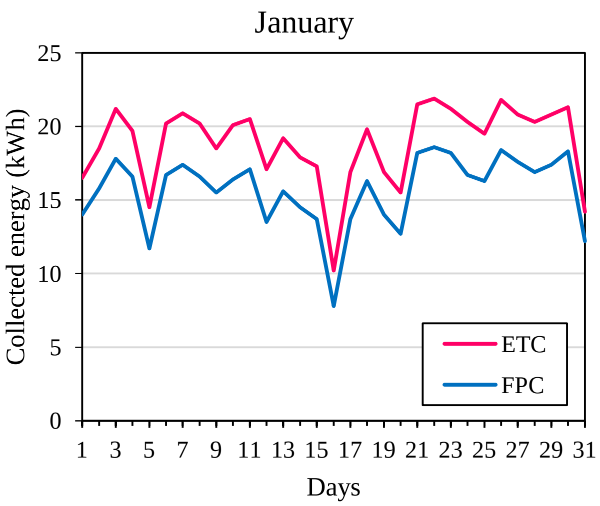
The collector's comparative thermal analysis is performed with four operating variables namely, weather conditions, volume flow rate, collector orientation angle as well as system size, to study how each variable's parameters affect the tank and collector outlet temperature, energy collected and accumulated in the tank and collector, efficiency and solar fraction of the system.

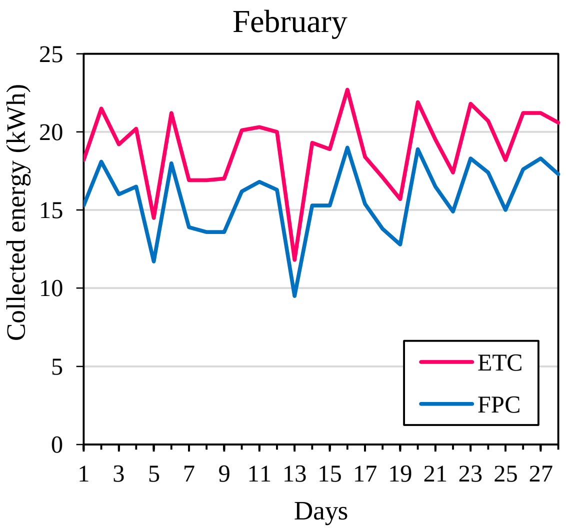
B.i. Effect of weather conditions

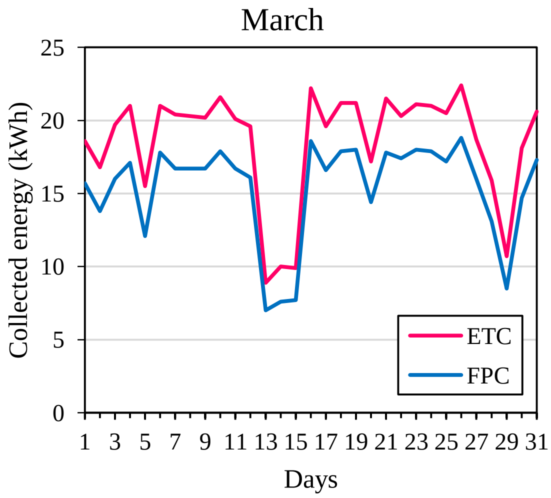
Fig. 5 shows trend of the changing energy collected by the collector that has been observed for all twelve months for a fluid circulating at 120 l/h, where the purple line represents ETC and the blue one is for FPC. For ETC, the maximum daily energy collected at the collector was found during November to be between 18 and 21.7 kWh/day and a minimum energy was collected in July to be between 6.1 and 18.2 kWh/day. FPC's maximum daily energy collected at the collector was found again in November ranging between 13 and 19.1 kWh/day while the minimum energy was collected in June to be between 3.9 and 15.5 kWh/day. Thus, November represented the highest monthly mean energy collected for both collectors, where, for ETC, the highest mean energy collected is 20.1 kWh/day (in November), and for FPC, the highest mean energy collected is 17 kWh. The total energy collected by the collector during November is 603.6 kWh/month and 510.3 kWh/month for ETC and FPC, respectively.

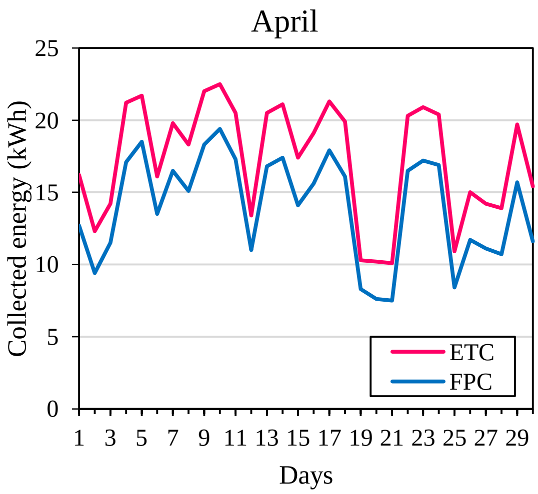
Averagely, ETC has collected an energy that is 15.4% and 16.8% more higher than that of FPC for June and November, respectively. It is apparent that, as solar radiation increases during summer season, so does the radiation absorbed by the absorber plate and the evacuated tubes, thus the energy gained by the solar collector increases. However, when the solar radiation increases the desired increase of efficiency may not be obtained due to the limit of absorption capacity of heat transfer fluids and increase of thermal losses.

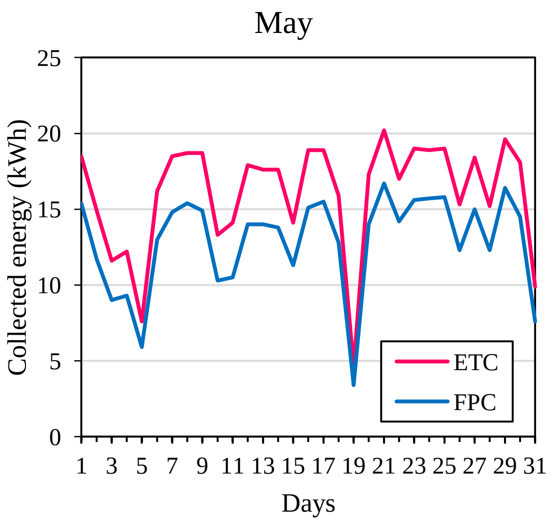
Fig. 6 shows the annual solar irradiation and the annual system solar fraction of both SWH systems, to demonstrate the actual effect of weather conditions on the solar fraction in a DHW system, by analysing the entire year of operation of such systems, including the periods characterized by less favourable weather conditions (lower solar energy inputs and lower ambient air temperatures). As it is shown in the figure, the solar fraction of both systems closely follow the profile of the global solar irradiation showing their dependency on the available solar energy.

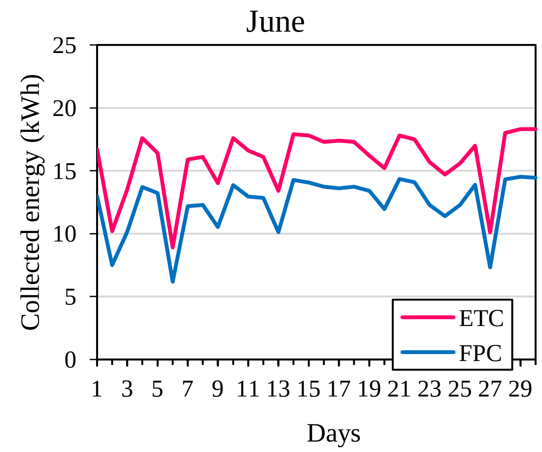


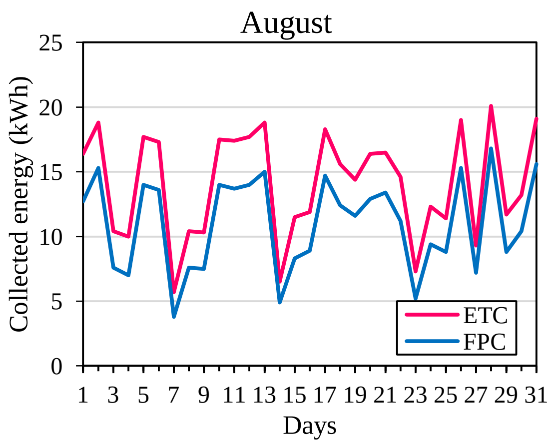


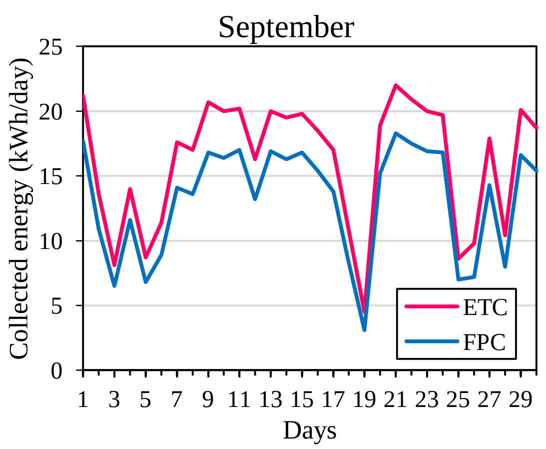


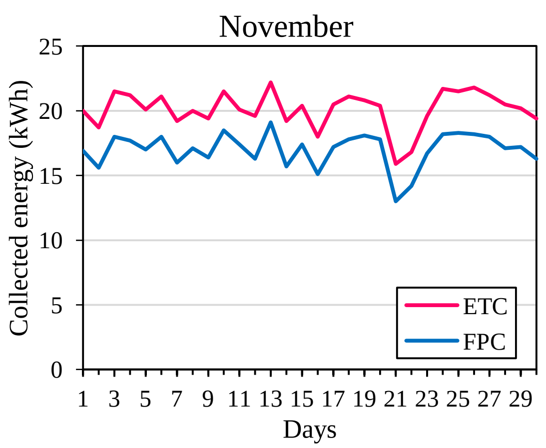












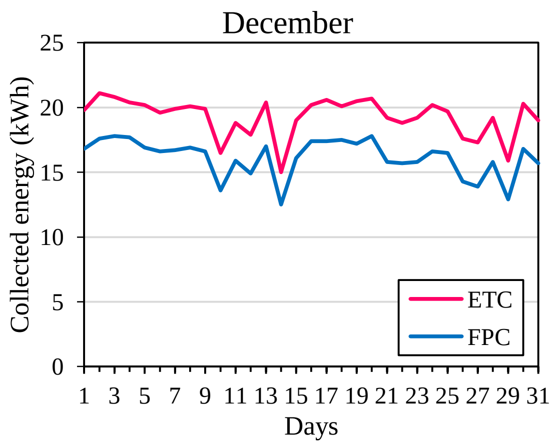


Figure 5. Daily energy collected by the collector for each month

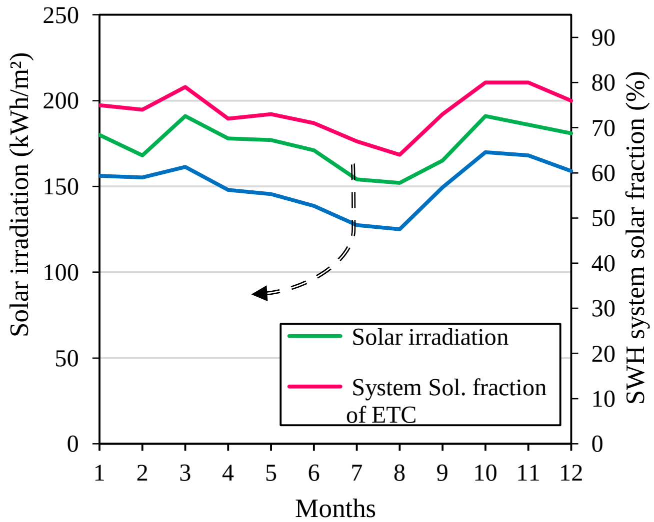


Figure 6. SWH System solar fraction at different solar irradiation throughout a year

The monthly solar fraction of ETC's system varied between 64% in August and 80% in November meanwhile, FPC's monthly solar fraction varied between 47.5% (in August) and 64.6% (in October). The lowest solar fraction was found during August ('Nehase' for Ethiopian calendar) at a solar irradiation of 152 kWh/m^2/month. It should be noted that this period includes only small portion of the annual insolation in the city of Adama, thus, a low solar fraction was expected. The highest solar fractions of both systems were recorded during March and November ('Megabit' and 'Hidar' in Ethiopian calendar) at a solar irradiation of 191 kWh/m^2. The higher energy collection in this period is primarily associated with the greater average solar energy elevation in spring months. As more favourable atmospheric conditions prevailed, higher values of radiation intensity will be observed. The aftermath is, temperature of the collector will be increasing and in turn a faster rise of temperature of water in the tank will be observed.
Hence, the system will be more capable of fulfilling the hot water demand.

The mean annual solar fraction in the case of ETC was 73.7%, while in the case of FPC it was 57.1%. Therefore, using ETC over FPC in this case improved the annual solar fraction by 22.5%.

Fig. 7 demonstrates each storage tank's hourly variations of outlet temperature of water for each month of a year. For a given day, the difference between the highest and lowest tank outlet temperature of each collector varies with each month. Out of all months, the highest tank outlet temperature of the water occurred in November, and the outlet temperature at this month varied between 43 and 87 °C for ETC, and 33.6 and 71.2 °C for FPC at 9:00 AM and 12:00 PM, respectively. Once again, the highest mean tank outlet water temperature was found in November to be 58 °C for ETC and 45.4 °C for FPC. These higher tank outlet temperatures are a result of a higher solar radiation intensity and higher ambient air temperatures that exist during this month (November). During this period, a large temperature difference will be developed between the air and the tubes which leads to a higher heat transfer rate from the air to the fluid, increasing the temperature of the fluid that is transferred to the storage tank. August gave the lowest mean tank outlet water temperatures of 38.2 and 33.8 °C for ETC and FPC, respectively. The lower outlet temperature were found during Winter months, because average ambient air temperature and the solar radiation intensity of this season are significantly lower than of other seasons. This results in a significant drop in the average daily temperatures of the water in the storage tank.

Fig. 8 shows the amount of energy collected by the two collectors throughout a day and it obviously shows, higher solar radiation will result in higher amount of energy collected by the collector that reaches its peak during noon and then decreases with the solar intensity. The ambient temperature causes significant variation in the net heat absorption capacity at higher solar intensity and the effect is relatively insignificant at lower solar intensity. For the total solar intensity throughout a day, ETC has collected an energy that is 18.6% higher than that of FPC. At noon, the daily solar irradiation on the active areas of the collectors can get as high as 4.19 kW and the energy accumulated in the collectors would reach 2.71 kWh/day for ETC and 2.26 kWh/day for FPC. Correspondingly, ETC and FPC collected 59.1% and 48.04% of the solar intensity throughout the day.

A higher solar intensity yields a higher rate of heat absorption by the working fluid. This is due to the fact that, when the ambient temperature increase with the solar intensity, the heat transfer rate to the fluid increases. In addition to that, with the rise of solar intensity, there is a significant increment in radiative heat transfer between the outer glass and the inner glass tube (for ETC) and between the glass and absorber plate for (FPC), hence there is an increase in net heat energy absorbed by the working fluid.

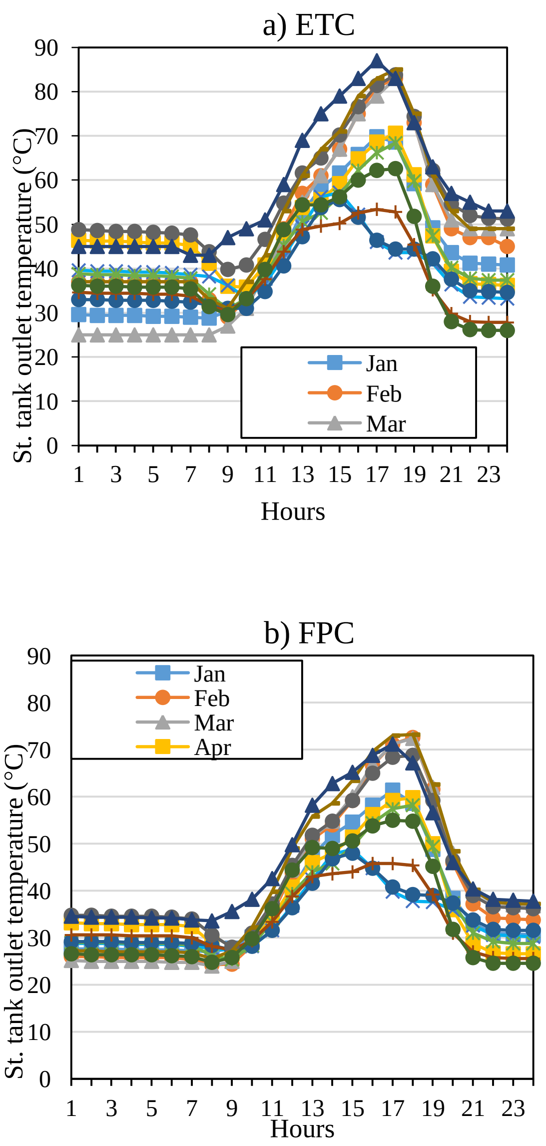


Figure 7. Hourly tank outlet temperature of ETC and FPC SWH system for each month

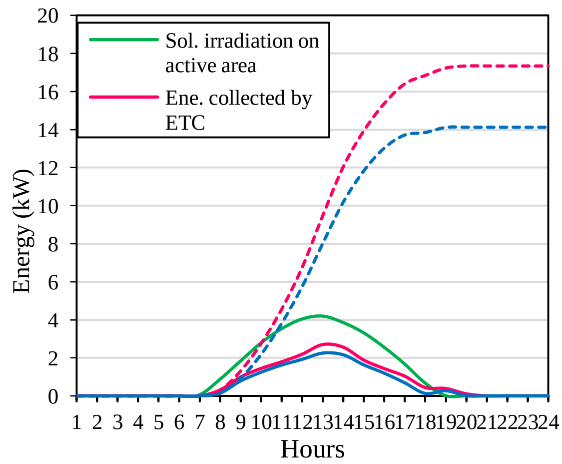


Figure 8. Influence of solar intensity on energy collected and accumulated by the collectors in a day

B.ii. Effect of volume flow rate

Fig. 9 compares the time wise variation of storage tank outlet temperature of water with different volume flow rates. Here, the analysis is done for volume flow rates of 80, 120 and160 *l*/h. For a particular day in April, at the highest flow rate (160 *l*/h), the tank outlet temperature of water can reach up to 74 °C and 62.5 °C for ETC and FPC, respectively. It is certain that increasing the amount of flow rate of the working fluid raises the tank outlet temperatures in each situation. For example for ETC, the mean tank outlet temperature has been improved by 14.06% as the volume flow rate is increased from 80 to 120 *l*/h, and by 6.36% as the volume flow rate is again increased from 120 to 160 *l*/h, also for FPC the mean tank output temperature of the fluid has been improved by 12.7% and 6.21% for the same respective flow rate boosts. The reason behind this is, though, at lower flow rates there is a longer period of contact between the working fluid and tube (heat pipe wall for ETC), it takes a while for the water to reach the storage tank, so in the meantime, it will lose much of its heat to the surrounding before it reaches the tank. But, at higher flow rate the fluid can quickly reach the tank without losing much heat and transfer it through the heat exchanger, hence there is an increase in the tank outlet temperature. The differences between the mean daily tank outlet temperatures of the two systems has been obtained indicating ETC's tank outlet temperature to be higher than FPC's by 20.3%, 21.5% and 21.6% for a volume flow rate of 80, 120 and 160 *l*/h, respectively.

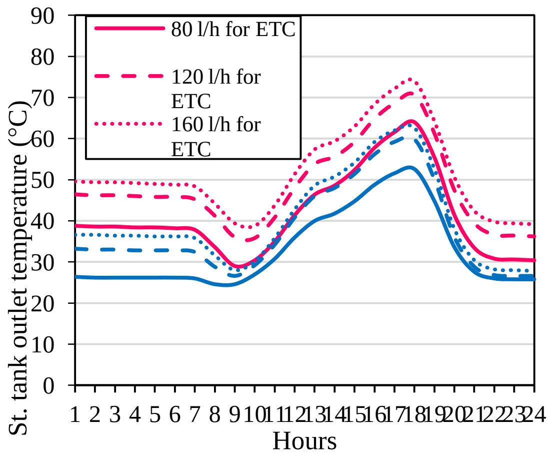


Figure 9. Storage tank outlet temperatures ETC and FPC for different flow rates on a typical day

Fig. 10 displays the variation of SWH system efficiency for different volume flow rates of the fluid as a function of the parameter T_i-T_a/I_T. This is a usual parameter for expressing the thermal efficiency of solar collectors. In comparative simulation of these two collectors, the highest SWH system efficiencies were achieved at a volume flow rate of 160 *l*/h for both ETC and FPC. This phenomenon is due to the decrease in the overall thermal loss of the collector at higher flow rates. Although the efficiency obtained at a flow rate of 80 l/h is low, it is a more preferable situation for the winter season. Nevertheless, a volume flow rate of 160 *l*/h emerges as a preferred value throughout a year, because it is at this volume flow rate that the highest efficiency of 59 and 50% could be achieved for ETC and FPC, respectively, at inlet water temperature of 22.5°C. ETC's system efficiency has shown to be higher than FPC's by 28.6, 21 and 18.21% for a volume flow rate of 80, 120 and 160 *l*/h, respectively. Increasing the inlet water temperature also reduces the efficiency of the system by 3 to 8% based on water inlet temperature. Both ETC and FPC presented a significant drop in the efficiency values at lower flow rates, since at lower fluid flow rates, the collector temperature rises and more heat will be lost out through the glazing and absorber plate (for ETC), then this heat loss reduces the heat output of the collector. However, high volume flow rates at low inlet water temperatures and solar radiation values can be disadvantageous since it can cause the outlet temperature to be lower, which is the basic purpose of SWHs.

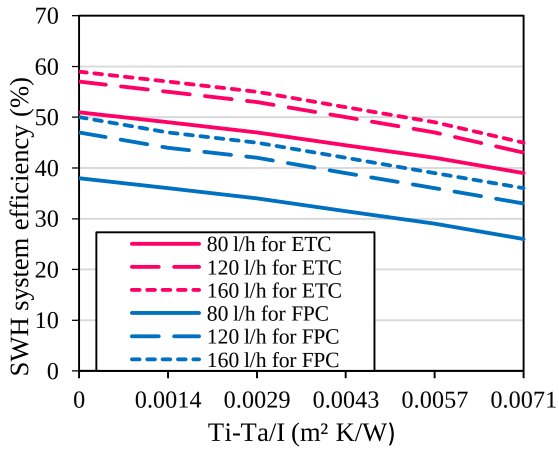


Figure 10. Variation of SWH system efficiency with different flow rates

Fig. 11 demonstrates the actual effect of fluid flow rates on the solar fraction in a SWH system. The solar fraction of both SWH systems increased with increasing volume flow rates. ETC's mean monthly solar fractions are 66.1%, 73.7% and 75.2% for 80, 120 and 160 *l*/h, respectively, while in case of FPC, the corresponding solar fractions becomes 47.5%, 57.1% and 60.1%. The monthly lowest and highest solar fraction of ETC's system exist during August and November, respectively, and lies between 57.8% and 72.2% for 80 *l*/h, between 64% and 80% for 120 *l*/h and between 65% and 82% for 160 *l*/h. In contrast, FPC's monthly lowest and highest solar fraction values existed for the same months as ETC's (August and November, respectively) and varied between 39.8% and 53.6% for 80 *l*/h, between 47.5% and 64.6% for 120 *l*/h and between 49.6% and 68.1% for 160 *l*/h. Hence, the lowest solar fraction was recorded at a flow rate of 80 *l*/h, in which it did not exceed 55% in both systems.

The highest system solar fraction of both collectors were found at a flow rate of 160 *l*/h, and for ETC, its value amounted to 82%, while, it is 68.1% in the case of FPC. Therefore, the use of high volume flow rates increased the energy absorption and usage of water in the storage tank, thus improved the annual solar fraction the systems averagely by 12.1% and 20.9% for ETC and FPC, respectively, when the flow rate is increased from 80 to 160 *l*/h.

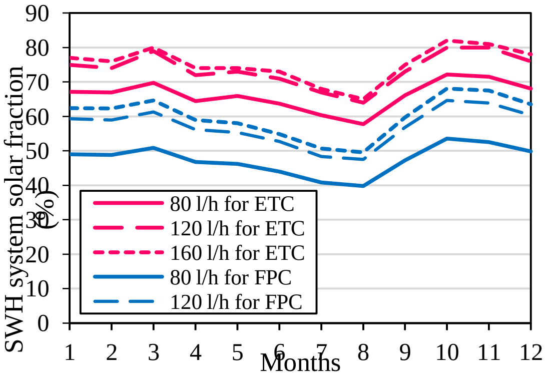


Figure 11. Variation of solar fraction with fluid flow rate throughout a year

V. V.CONCLUSION

In this study, an hourly, daily, monthly and seasonal year-round thermal performance analysis of a commonly used SWH systems with ETC and FPC was carried out by using T*SOL® Pro simulation programme. The analysis of the SWH system regarding the estimation of the daily heating load was based on domestic hot water demand. The influencing characteristics of the volume flow rate and weather conditions were discussed in details.

The results from the study showed, that the system efficiency, solar fraction and tank outlet temperature increased with the volume flow rate due to the increase in the heat supplied to the fluid. Thus, it can be concluded that the collectors will be more efficient operating at relatively high flow rates such as 160 *l*/h, but there will only be a low collector outlet temperature rise. If the flow rate is decreased all the way to 80 *l*/h, collector outlet temperature rises. However, more heat will be lost to the surrounding through the glazing, tubes and absorber plate, and these losses reduce the heat output of the collectors.

The monthly total solar radiation, incident on the collector surface have a maximum value during October to December and minimum value during July to August. Sunny seasons and warmer climates are usually associated with higher water temperatures since, higher solar radiation will result in higher amount of energy collected by the collector. Despite the promising effects of the use of SWHs, this study showed that during the colder season it was difficult to obtain satisfying water temperatures in the storage tank in the cases of both systems. Water inlet temperature can be associated with weather condition and at higher inlet temperature, the useful energy collected will decrease. Overall, Evacuated tube collectors proved to be a more efficient collector at any water flow rate of and in every season.

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AUTHORS PROFILE

Mr. Abdi Chimdo, born in Adama, Ethiopia on 8th April 1994, completed Bachelor of Engineering (Mechanical Engineering) in the year of 2016 from Adama Science and Technology University and completed Master of Engineering (Thermal Engineering) in the year of 2018 from Adama Science and Technology University. He has published one article in international journal. His research area is solar energy, thermal collector and solar water heating systems.

Dr. Chandraprabu Venkatachalam, (Corresponding Author) born in Tiruchengode, Namakkal (DT), Tamilnadu, India on 25th January 1977, Completed Bachelor of Engineering (Mechanical Engineering) in the year of 1999, completed Master of Engineering (Thermal Engineering) in the year of 2005 and completed PhD (Thermal Engineering) in the year of 2014. He has published seven articles in international journal, three articles in international conference and seven articles in national conferences. His research area is heat transfer enhancement in air conditioner using nanofluids and solar energy.

Dr. Addisu Bekele, Completed B.Sc. Degree in Mechanical Engineering in 2004, from Bahir Dar University, Ethiopia, M.Sc. Degree in Mechanical Engineering (Thermal) in 2007 from Addis Ababa University, Ethiopia and PhD Degree in Thermal Engineering in 2012 from Indian Institute of Technology, Roorkee, India. He has published more than 11 articles on international journals, international conferences and national conferences. His research interest areas are renewable energy, fluid flow and heat transfer.

Dr. Mohanram Parthiban, born in Sendamangalam, Namakkal (DT), Tamilnadu, India on 19th June 1978, Completed Bachelor of Engineering (Mechanical Engineering) in the year of 2000, completed Master of Engineering (Thermal Engineering) in the year of 2004 and completed PhD (Thermal Engineering) in the year of 2015. He has published four articles in international journal, an article in international conference and two articles in national conferences. His research area is heat transfer, solar energy and thermal energy storage systems.