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Configuration Selection of Solar Collector and Thermal Storage System for Domestic Refrigeration Applications

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ABSTRACT

Solar water heating (SWH) systems becomes an essential part in modern buildings, reducing the energy consumption substantially for heating applications. This study reports the predicted monthly averaged thermal performance of SWH system integrated with sensible thermal energy storage (TES) system, in terms of solar fraction using TRNSYS software. Under similar weather conditions, the results of transient simulations show a deviation of 8.1 % with respect to experimental results. Placing the compound parabolic concentrator (CPC) collector under evacuated tube (ET) enhances the useful energy gained by 5 % passively. Design and operating parameters of SWH system are analyzed with different controllers for achieving optimal performance. Results show a significant influence upon increasing aperture area on solar fraction up to certain limit, minimizing the cost through proper selection of collector area. For a particular volume of TES system, simulations are performed for attaining maximum solar fraction at different mass flow rates of heat transfer fluid, followed by varying the aspect ratio of TES system. The proposed system can supply the hot water demand of 280 $l\ d^{-1}$ at 60 °C, reaching a solar fraction of 0.97. This design strategy can be implemented towards development of an efficient SWH system, utilizing zero energy consumption from conventional resources.

Keyword: TRNSYS, CPC solar collector, stratified thermal storage tank, optimization, thermal energy storage.

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1. INTRODUCTION

Solar energy is the most promising renewable energy source in terms of its abundant availability, emitting at the rate of 3.8×10^{23} kW, out of which the earth intersects only 1.8×10^{14} kW (Kalogirou, 2014). Harnessing of solar energy depends mainly on absorption and its conversion into heat energy using a network of collectors. Flat plate and Evacuated tube (ET) collectors are broadly used in medium temperature applications. However, the requirement of a larger collector area, low optical efficiency and abundant loss of useful heat gained reduce the overall efficiency of the system. A non-tracking concentrated solar collector, consisting of ET with parabolic reflectors called as Compound Parabolic Concentrator (CPC) collector, is employed in solar water heating (SWH) system for overcoming the above stated major drawbacks. These collectors operate over a wider operating temperature range, capable of collecting both direct beam radiation and part of diffuse radiation. Water is used as heat transfer fluid (HTF) in the domestic SWH system, due to its desirable thermal transport properties, compatibility with the collector material and its availability. However, there is a considerable reduction in thermal efficiency of any collector with respect to rise in temperature of the HTF at the inlet, resulting in temperature lift at all sections of the collector.

There are components both in the standard library of TRNSYS components and the TESS Libraries that are very useful for TRNSYS SDHW simulations. Components for water draw profiles, storage tanks, controllers, valves, pipes, pumps, and collectors may be implemented in the Simulation Studio graphical interface just as the mechanical diagrams of the actual system. Product design and optimization is a process of interpolation through iteration. Rating and certification process involves thorough testing of the product in standard test conditions.

But real world experiments are full of variations and uncertainties. Moreover, it is not feasible to create extreme testing environments in laboratory experiments.

In many cases physical experiments are not possible at all due to excessive run duration, trade off and socio-financial implications. In such cases simulation is a promising alternate for performance analysis and design optimization. Professionals and researchers also face similar problems while working on solar energy system. There is a fast growing market of solar water heater worldwide. Solar water heating system is transient in nature and its performance depends on dynamic parameters.

TRNSYS model of a solar generation

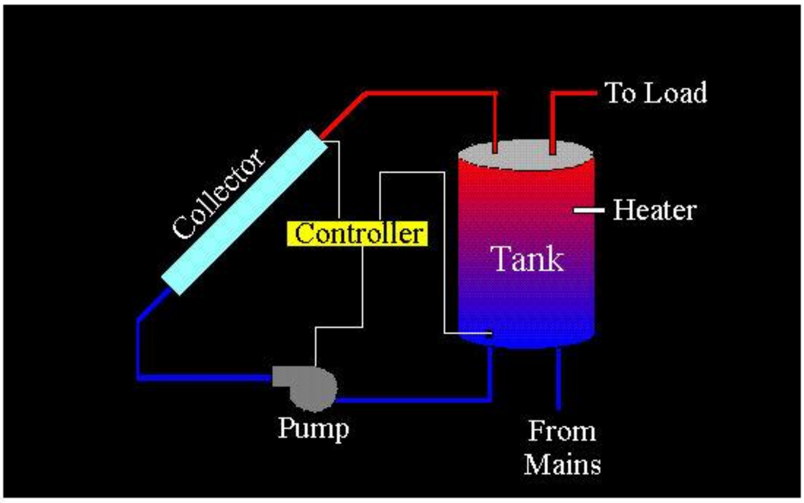


Fig : 1.1

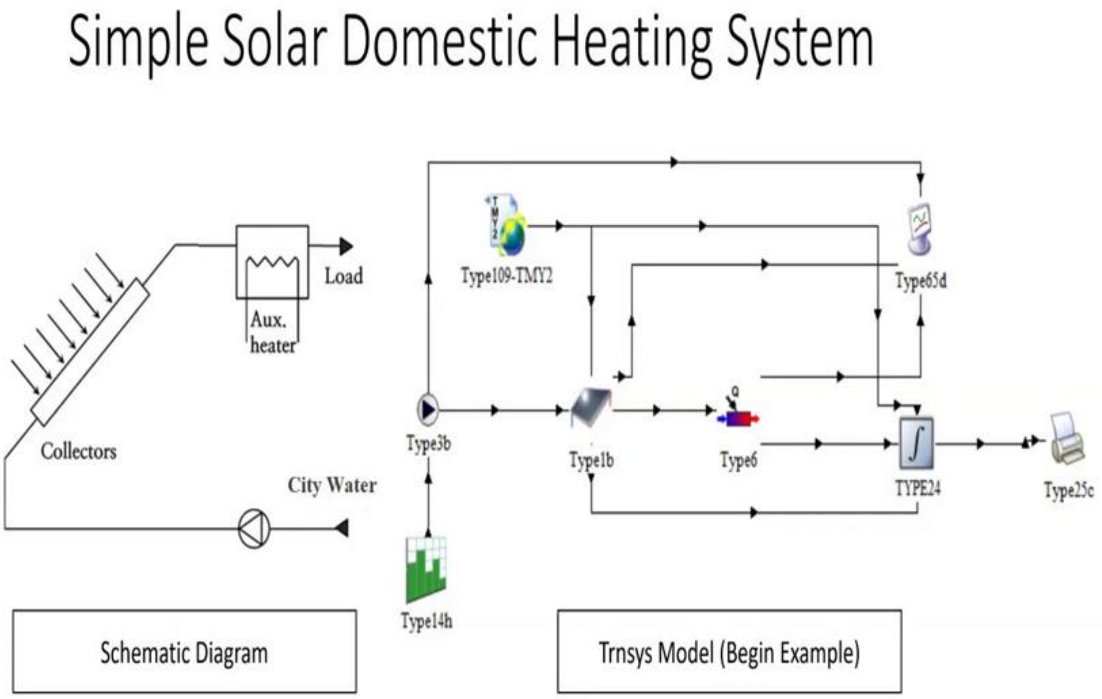


Fig : 1.2

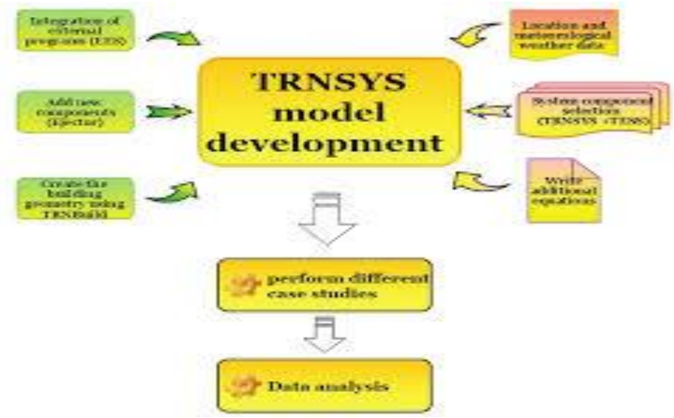


Fig : 1.3

TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. It is used by engineers and researchers around the world to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, hydrogen systems), etc.
One of the key factors in TRNSYS' success over the last 25 years is its open, modular structure. The source code of the kernel as well as the component models is delivered to the end users. This simplifies extending existing models to make them fit the user's specific needs.

The DLL-based architecture allows users and third-party developers to easily add custom component models, using all common programming languages (C, C++, PASCAL, FORTRAN,etc.). In addition, TRNSYS can be easily connected to many other applications, for pre- or post processing or through interactive calls during the simulation (e.g. Microsoft Excel, Matlab,COMIS, etc.).

SYSTEM CONNECTIONS

Type109 (Weather data) to Type1 (Solar collector)
• Ambient temperature → Ambient temperature
• Total radiation on horizontal → Total horizontal radiation
• Sky diffuse radiation on horizontal → Horizontal diffuse radiation
• Total radiation on tilted surface → Incident radiation
• Angle of incidence for tilted surface → Incidence angle
• Slope of tilted surface → Collector slope
Type 14 (Forcing Function) to Type 3 (Pump)
• Average value of function → Control signal
Type 3 (Pump) to Type 1 (Solar collector)
• Outlet fluid temperature → Inlet temperature
• Outlet flow rate → Inlet flow rate
Type 1 (Solar Collector) to Type 6 (Auxiliary heater)
• Outlet temperature → Inlet fluid temperature
• Outlet flow rate → Inlet flow rate

To obtain the satisfactory and consistent performance of solar water heating (SWH) system needs enough sizing as well as precise prediction of the thermal behavior of each component in the system. Therefore, it is essential to optimize the system in order to get better performance from each component of the system. The major component of SWH system is a solar collector, which can be considered as a heat exchanger that can collect solar collector and transfer into HTF flowing through the collector. The performance of the SWH mainly depends on the effectiveness of the solar collector, which is influenced by the type of solar collector. The most commonly used solar collectors are a flat plate, evacuated tube and concentrating solar collector. However, for the non-concentration solar collector such as evacuated tube and flat plate solar collector, with an increase in temperature, the thermal efficiency of the collector deteriorates. Particularly more than 80 °C, Therefore, it requires solar concentrators, as opposed to non- concentration solar collectors**[1]**. Moreover, the high-concentrated solar collector can meet the energy demand; they required tracking system, which increases operation and management cost, and higher concentrated ratio collector makes more diffusion loss, which will not fit for the medium application. Besides, the compound parabolic concentrator (CPC) is a non- imaging solar collector having ability to reflect most of the incoming radiation to the absorber. It can attain a temperature of more than 80 °C with reasonable thermal efficiency compared to non - concentrated solar collector.

The performance evolution of CPC collector is theoretically and experimentally investigated for past decades. For instance, In the 1970s, **Winston** [2]developed newer techniques for collecting and concentrating the solar radiations, in which trough-shaped cylindrical collector is kept with large acceptance angle. As sun radiation can fall on a receiver for 8 hours per day. The first generation of the evacuated CPC collector was developed at the **Argonne National Laboratory** [3].In this model, CPC was integrated with the Dewar-type evacuated tube. **O'Gallagher et al.**[4,5]developed a modern version of CPC solar collector in which collector design has an ability to have least price path to a non-tracking higher heating temperature .i.e. >200. **Hsieh et al** [6,7]made a detailed study on thermal analysis for CPC solar collector and proposed empirical relation for heat loss coefficient. **Rabl**[8,9]**.**Studied the optical effect on CPC solar collector under wide acceptance band. It is recommended to use a constant value for an average number of reflections in all incident light falls over the aperture area of CPC solar collector for engineering purposes. **Widyolar et al** [10]evaluate the feasibility of CPC solar collector by providing power to LiBr-H_2o absorption chiller and this was the first system to integrate with double effect solar refrigeration system with a temperature of up to 200 °C. However, the above literature shows that the performance of CPC collector is studied under simplified working conditions and this performance study has been taken in particular climatic conditions.

SCHEMATIC REPRESENTATION OF SOLAR WATER HEATING

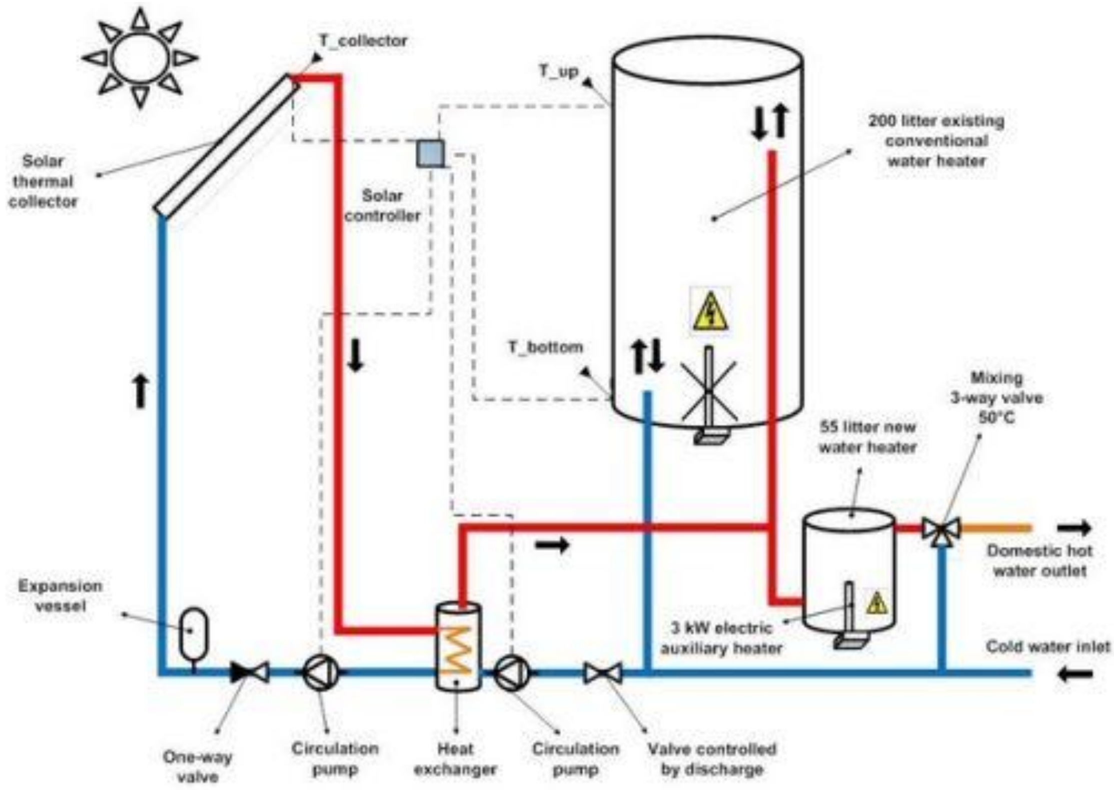


Fig 2.1

SCHEMATIC REPRESENTATION OF SOLAR HEAT GENERATION

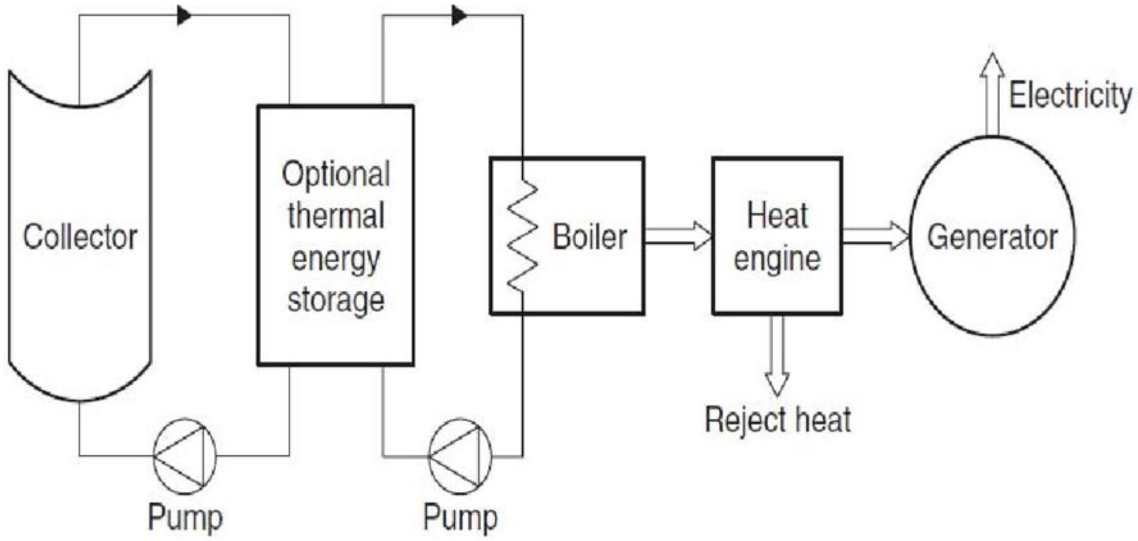
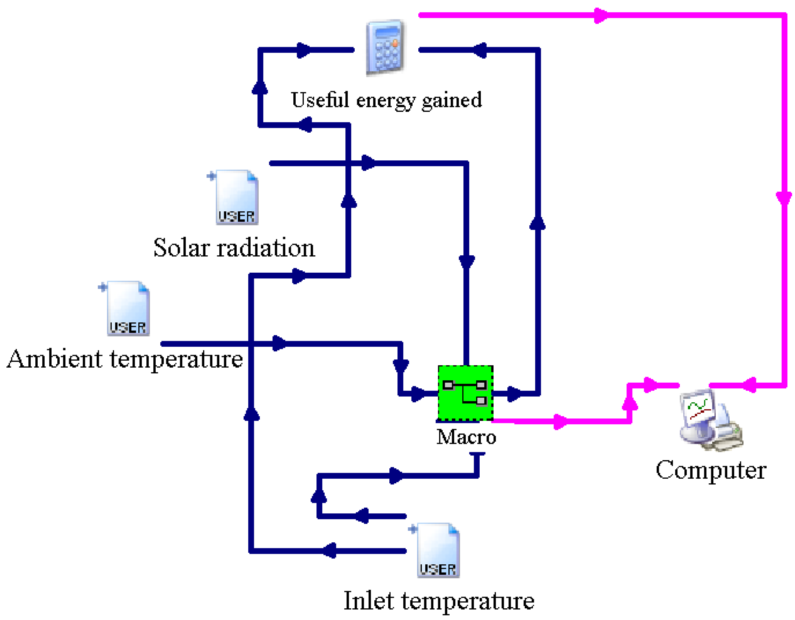


Fig 2.2

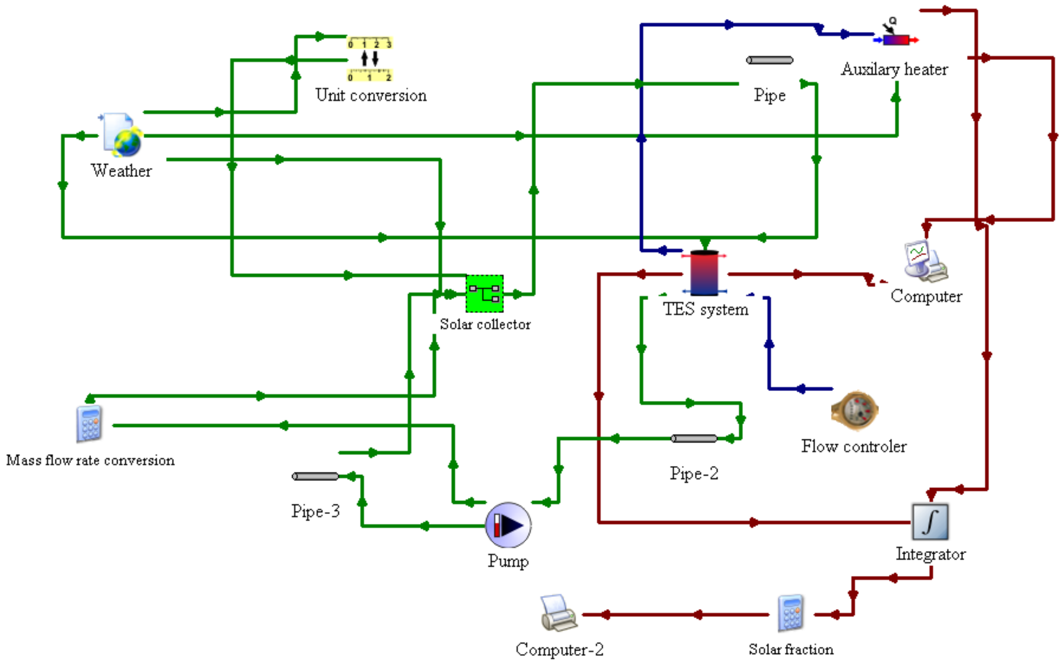
SYSTEM DESCRIPTION

Fig (a-d) is the TRNSYS flow diagram for SWH system, including an ET liner model (Equation folder 1), CPC liner model (Equation folder 2), pump (Type 3d), TES tank (Type 4b), expert mode (Type 9a), pipe (Type 31), integrator (Type 25c), online plotter (Type 65c), printer (Type 25c), weather data (15-6) and differential controller (Type 2d). At start of the simulation, HTF was pumped from the bottom of the TES system to the CPC solar collector in the charging cycle. Subsequently, hot water entered at the top of TES system, charging by direct mixing of HTF with water already present in the TES system. During discharging cycle, HTF (water) from the makeup water tank was pumped to the bottom of the TES system, for mixing directly with hot water. The simulations were carried out using TRNSYS software with a one-hour time step and the simulation technique of the successive approach was taken into consideration to obtain a suitable sequential solution. The programme was dveloped as given in annexure for varying the flow rate of HTF in the ET-CPC collector for achieving the uniform outlet temperature of 85 °C under charging conditions.

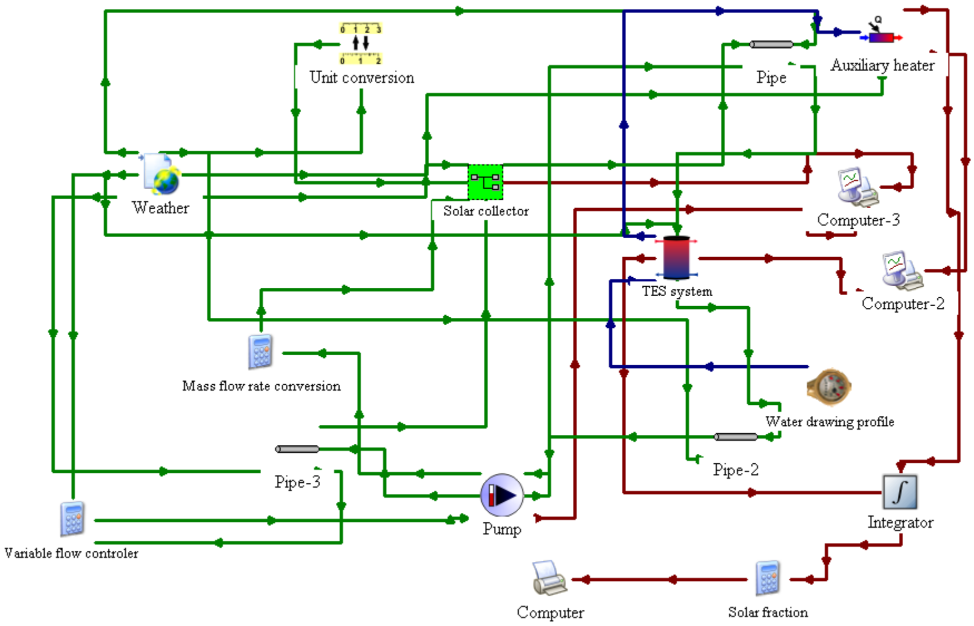
(a) Fig 2.3



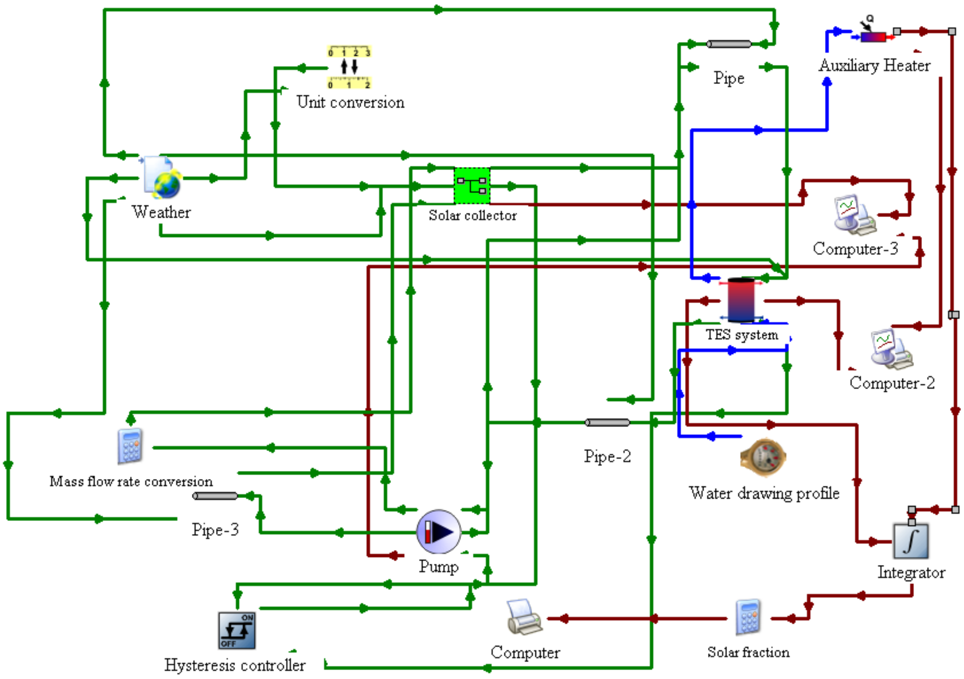
(b) Fig 2.4



(c) Fig 2.5

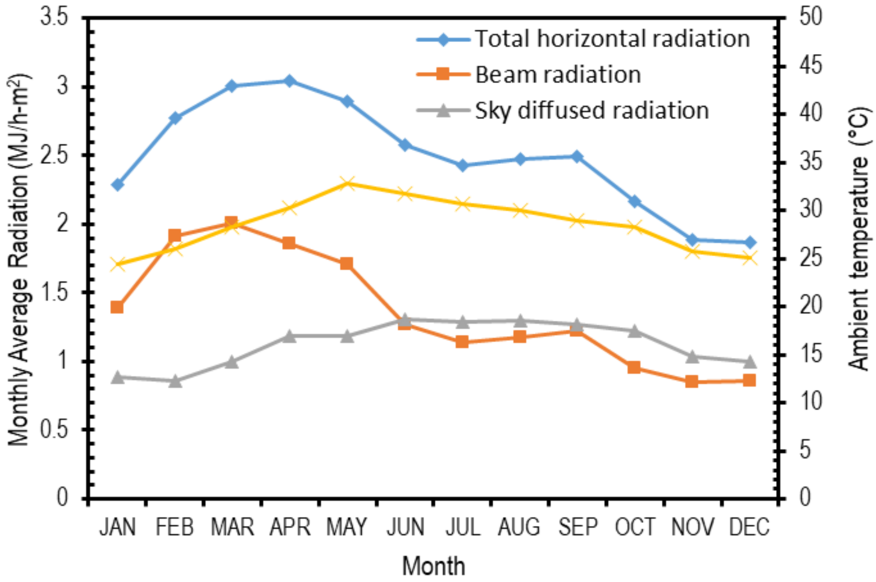


(d) **Fig 2.6**



Flow diagram of SWH system (a) for charging cycle (b) without controller (c) with variable controller (d) with hysterises controller

The climatic data base is taken from Typical Meteorological Year (TMY) for madras conditions. The variation of average temperature distribution for one year as shown in **Fig 3.1.** The average minimum and maximum temperature occurs at May and January and the temperature is 33 °C and 24 °C. The variation of diffused, beam, total radiation for one year is depicted. The average solar radiation reaching surface of the solar collector is around 25.20 MJ/hr-m^2.

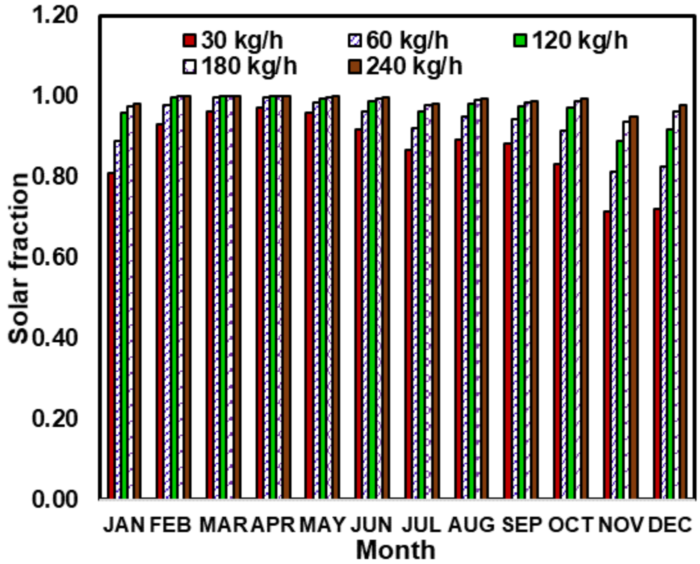


Monthly average solar radiation and ambient temperature distribution for Madras area

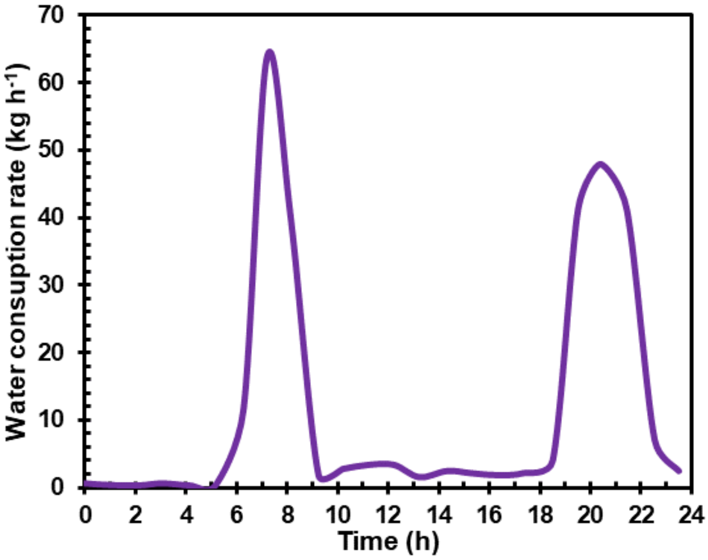
2. RESULT AND DISCUSSION

Optimization of system parameters
Effect of mass flow rate in the solar collector.

The computed results of solar fraction at different flow rates of 30 - 240 kg h^{-1} are shown in Fig 9 for the collector aperture area of 6 m^2. As noticed from the figure, the monthly average solar fraction shows the upward trend with increasing flow rate, resulting a maximum of 0.97 in the month of April. Only, a small increase in solar fraction is observed with further increase in the flow rate, indicating the unfavorable operating conditions with regard to hot water collection compound parabolic collector demand as illustrated in Fig 10. The annual average solar fraction is incremented to a maximum of 0.87 - 0.96 as the flow rate increases from 30 kg h^{-1} - 120 kg h^{-1}. This is because of a considerable gain in energy output with increasing mass flow rate, that also reduces the associated heat losses due to lower temperature driving potential between the solar collector and ambient. An insignificant increase in solar fraction of only 0.5 - 2 % is seen, while the flow rate is maintained above 120 kg h^{-1} due to destratification in TES system. From the above discussion, the HTF flow rate of 120 kg h^{-1}, which yields the most favorable solar fraction is considered for further analysis.



Solar fraction at different mass flow rates of HTF.



Domestic hot water demand (Ahmed et al., 2016).

Effect of storage tank volume and height:

Flow rates of the HTF has the considerable impact on the size of TES system because of the variation in its resident time. Firstly, keeping height of the TES system as 1 *m*, series of simulation have been carried out by varying the volume of the TES system between 280 - 310 *l* and the results are presented in Table 2. As expected, a negligible change in solar fraction is observed up to 290 *l*. However, further increase in volume of TES system results with a reduced solar fraction, which could be attributed to the higher heat loss from the TES system. For the considered simulation, the variation in solar fraction exhibits a declining trend above 290 *l* and so an average TES volume of 285 *l* is taken to analyses the effects of height of TES system. As seen from Table 2, on increasing the height of the tank at the end of the system start from 0.2 m to 1.2 m augments the solar fraction from 0.9 to 0.97, owing to better thermal stratification resulting from a higher aspect ratio of TES system. This effect is almost insignificant, when the height of TES is above 1.2 m, exemplifying the fully stratified behavior of TES system. On this basis, the TES system of 1.2 m height and 285 *l* volume is the favorable option compared with the other cases for better utilization of solar energy.

TABLE 1 Variation of solar fraction for different TES dimensions

Fixed parameter	Varying parameter	Solar fraction
$\dot{m}$ = 120 $kg\ h^{-1}$ L = 1 m	V=280 *l*	0.960
	V=285 *l*	0.961
	V=290 *l*	0.961
	V=295 *l*	0.950
	V=300 *l*	0.945
$\dot{m}$ = 120 $kg\ h^{-1}$ V = 285 *l*	L = 0.6	0.900
	L = 0.8	0.940
	L = 1.0	0.961
	L = 1.2	0.965
	L = 1.3	0.967
	L = 1.4	0.968
	L = 1.5	0.968
	L = 1.6	0.969
	L = 1.7	0.970
	L = 1.8	0.972

Thermodynamic study on each component of the optimized system.

The above optimization technique can give the information related to complete system but to examine the individual component it is necessary to use an energy and exergy techniques. Based on these techniques the thermal performance of collector and storage tank were studied.

Thermal performance of CPC solar collector

To study the thermal behavior of CPC solar collector for complete year. The collector area, mass flow rate of solar field HTF, storage tank volume and storage tank height is taken from the above section 5.1 and for the present study collector tube is considered to be coated with $TINO_X$ on the absorber tube. The performance summary of CPC solar collector over a period of a year given in Table 2. The result shows that optimum collector can have minimum efficiency of 54 % during December and maximum efficiency of 63 % during period of April but annually solar collector can attain an efficiency of 58 %. The result also shows that collector can attain a maximum and minimum outlet temperature of 134 °C and 85 °C in March and December. The monthly variation of inlet and outlet temperature, energy gain from the solar collector, solar radiation vary between 30-34 °C and 134-85 °C, 14.3 -26.5 MJ/hr, 26.1-42.5 MJ/hr. The variation in these parameters obtained for a XCPC solar collector indicates that these parametric factors are strongly influenced by the temperature difference between the surrounding and solar radiations falls on the solar collector.

The thermal performance summary of CPC solar collector

Month	Inlet average temperature (°C)	Outlet average temperature (°C)	Monthly average energy gain (MJ/hr)	Average solar radiation (MJ/hr)	Efficiency
JAN	30.1	101.9	18.73	32.01	0.59
FEB	32.8	126.4	24.46	38.77	0.64
MAR	33.9	134.4	26.54	42.11	0.63
APR	34.6	133.7	26.15	42.56	0.61
MAY	34.2	128.2	24.44	40.41	0.60
JUN	34.5	113.5	20.	36.11	0.58
JUL	34.3	107.2	19.26	33.97	0.57
AUG	33.8	108.1	19.63	34.60	0.57
SEP	33.2	108.6	19.90	34.92	0.57
OCT	34.5	113.5	20.	36.11	0.58
NOV	31.0	86.1	14.55	26.44	0.55
DEC	32.8	125.4	24.46	38.77	0.63
AVG	**33.4**	**110.6**	**20.46**	**34.48**	**0.60**

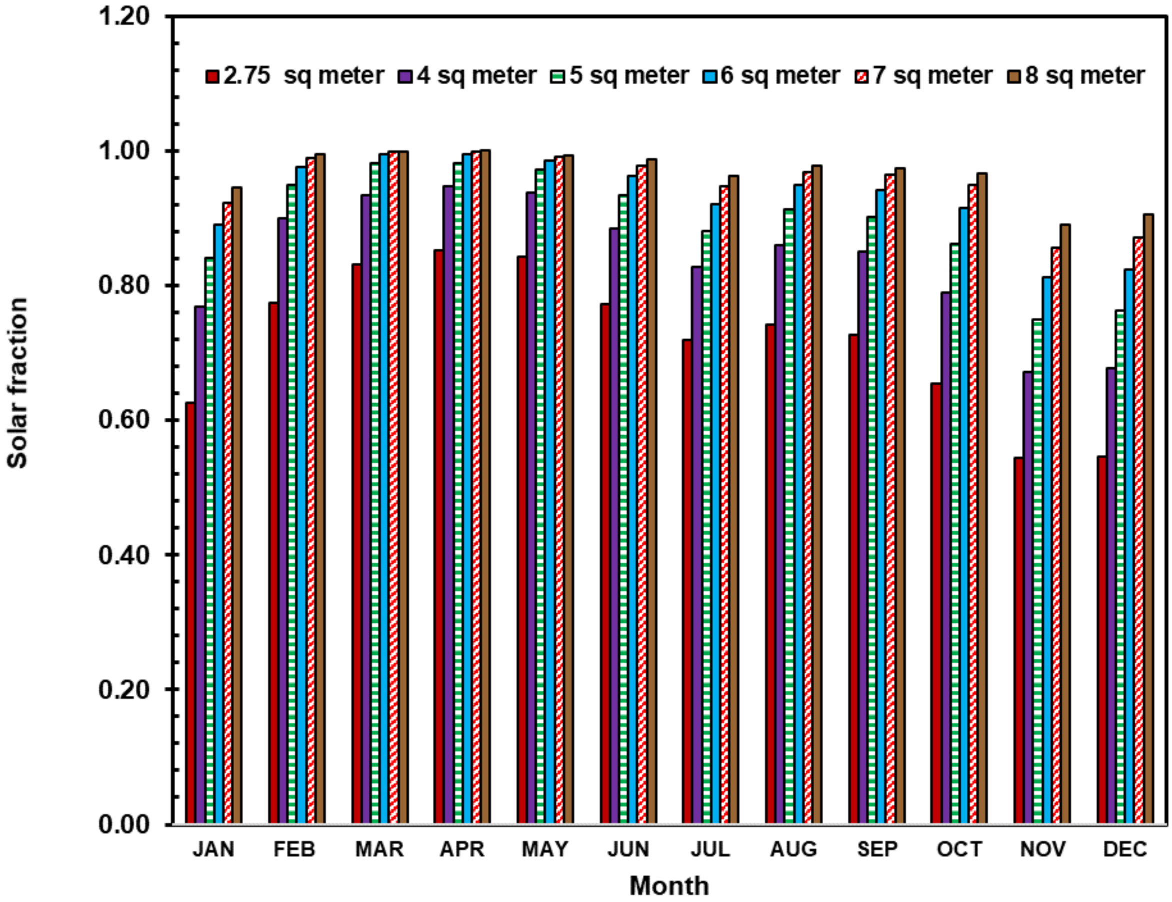
Stratification temperature with in the tank

In a thermally stratified storage tank, the temperature of the contained liquid varies from the top to bottom, being higher at the top and lower at the bottom. The thermal stratification is desirable if the temperature difference is significant. In this investigation, the storage tank are divided in to 5 nodes, the flow to the collector constantly leaves from the bottom node 5, and the flow to the load constantly leaves from the top node 1. The rest of the layer are formed in between the 1 and 5 nodes; each node has a distance of 0.2 m. Due to the these configuration, the thermal energy losses from the storage tank is considerably reduced and second advantages is that CPC solar collector operates at lower inlet temperature and enhance the maximum collection of collector efficiency.

Describes the temperature variation of thermally stratified storage tank for optimized solar water heating system during month of May. The plot indicates for the given configuration, the temperature profile appear to reaching steady state value at about 3- 4.5 hour mark. The graph also shows that, during steady state temperature at top node is twice greater than bottom node.

Effect of aperture collector area:

The effects of varying the collector aperture area from 4 m^2 to 8 m^2, with step size of 1 m^2 on solar fraction have been computed under the same weather conditions present and the results are present shown in Fig . Firstly, the variation in solar fraction on monthly basis is evaluated for the area of the collector aperture by using various factors area of 2.75 m^2 and it has been ranging between 0.65 - 0.85, as displayed in Fig 8. Looking at the figure, monthly averaged solar fraction of nearly 0.9 - 1 is attained for the solar collector with 8 m^2, which can be attributed to a higher useful heat energy gained in the collector for a particular available solar radiation. Further, it can be seen that an increase in average annual solar fraction of 14 % with an increase in collector area from 2.75 m^2 to 4 m^2 at 60 kg h^{-1}. As expected, the solar fraction exhibits an increasing trend with respect to increase in collector area as it has a direct bearing on heat transfer rate. However, the trend is not in proportionate to increase in collector area. As perceived, solar fraction augments only by 1.3 % when the area varies from 7 m^2 to 8 m^2, but significantly improves by 10 % when the area varies from 4 m^2 to 5 m^2. On comparing the results, there is insignificant gain in solar fraction after the collector area increases above 6 m^2. The collector area is the vital one, particularly in domestic application, where the space is more constrained. Over sizing also involves redundant heat losses and higher capital cost. From the parametric analysis, the optimal collector area is taken as 6 m^2, exhibiting more sensitivity to solar fraction without compromising the thermal performance. 6



Monthly averaged solar fraction for different collector areas

3. CONCLUSIONS

Thermal performance of SWH paired with sensible TES system is analyzed under transient conditions using TRNSYS for the whole year. The major design and operating parameters of SWH system are evaluated at climatic conditions of Chennai. Water is circulated to transfer heat from the solar collector to the TES system, catering to a hot water demand of 280 $l\ d^{-1}$. The experimental and numerical results are relatively close, establishing the validity of TRNSYS model. Monthly averaged solar fraction of SWH system exhibits a better performance using hysteresis controller. A maximum increase in solar fraction of 26.3 % is obtained by increasing the aperture area from 2.75 m^2 to 6 m^2 at a constant HTF flow rate and further increase in area has almost no effect on solar fraction. Based on that, the HTF mass flow rate is optimized as 120 kg h^{-1}, performing better in the month of April and May and reaching an annual average solar fraction of 0.96. The simulations carried out make it possible to design the volume and height of TES system for attaining the higher degree of thermal stratification and thereby augmenting the thermal performance of collector. The proposed system is capable of supplying hot water even during the night hours, alleviating the major challenges in other SWH systems, particularly for building applications. In conclusion, SWH system can be sized based on the solar fraction arrived from the satisfactory prediction of long term performance using TRNSYS model. Multi-design optimization and smart control strategies in SWH system remain to be explored for improving its thermal performance, while minimizing the capital cost and it will be the main focus of future work.

REFERENCES

[1]. C.cristofari ,G.Notto,,P,Poggi " Modelling and Performance of a copolymer Solar Water Heating Collector "Solar Energy ,Vol 72, N°2, 2002, pp .99

[2]. Runsheng Tang,Yanbin Cheng Maogang Wu "Experimental and odeling studies on thermosiphon domestic solar water heaters with flat- plate collectors at clear nights" Energy Conversion and Management ,Vol 42 , 2003, pp 455-469 .

[3]. Alireza Hobbi,Kamran Siddiqui "Optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS", Solar Energy ,Vol 82, 2009 , pp 700-714.

[4]. A.Zerrouki,A.Boumédien, K.Bouhadef " The natural circulation solar water heater model with linear temperature distribution" Renewable Energy ,Vol 26, 2002, pp 549-559.