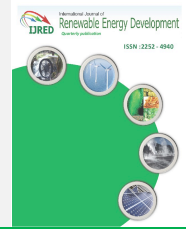




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Research Article

Design and Performance Evaluation of a Multi-Temperature Flat Plate Solar Collector

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ABSTRACT. The standard flat-plate solar collector utilises a single copper tube to remove the absorber plate's heat. This type of collector's primary purpose is to provide hot water for a single application. Hot water can be required for different applications at different temperatures. Besides, using the standard collector's configuration may increase thermal demand and increase the collector's size. Therefore, this study proposes a novel solar water heating configuration that uses three in-line fluid passages. The goal is to design a single collector that provides hot water for various uses: Sterilisation, washing, and postnatal care. Thus, the proposed system was modelled, and a numerical simulation conducted. This analysis compares the proposed system's output and the standard collector's output. The results showed that the thermal load demand was reduced by 27% when the hot water demand for these services was generated using three separate tanks. The serpentine collector's efficiency with three fluid passages is increased by 20% compared to the traditional serpentine collector. The thermal energy delivered to meet load was 30% higher than that of the traditional serpentine system. The experimental and simulated system performance is in near agreement with an average percentage error Cv(RMSE) of 8.75% and confidence level NSE of about 87%. Since the proposed serpentine collector has a higher overall thermal production, it is recommended for use with hot water, which has to be heated to different temperatures.

Keywords: : Solar water heater, Serpentine collector, Simulation, Collector efficiency, Solar fraction

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1. Introduction

Solar energy is the best gift to humanity and the world's most abundant renewable and cheapest energy source. The estimated power from the sun intercepted by the earth is approximately 1.8×10^{11} MW daily, which are thousands of times larger than the world energy consumption rate of all commercial energy resources (Sukhatme, 2009). A good guess puts the annual energy received on the earth at about 2,895,000 EJ annually, which is greater than total non-renewable energy sources of about 325,399 EJ (World Energy Council, 2004). Thus, in principle, solar energy could supply all the present and future energy needs of the world continually if only 10% of the solar energy can be harvested (Memon *et al.*, 2020). The solar thermal energy system is a viable energy alternative which can reduce hot water demand in health centres and cottage industries (Olatomiwa, 2016; Olatomiwa, Mekhilef and Ohunakin, 2016; Ohijeagbon *et al.*, 2019). Even though solar energy holds the potential to transition to low carbon energy sources, many are still

required to promote adaptability in many locations. Madvar *et al.* (2018) discuss essential energy policy and security issue based on the Iranian scenario that will accelerate the deployment and installation of renewable energy systems. Solar water heating systems have shown in many ways to reduce hot water energy consumption significantly. One primary concern that has attracted much research is the solar water heaters' low energy conversion efficiency (Deng *et al.*, 2019; Eltaweel, Abdel-Rehim and Hussien, 2020).

Consequently, many studies have been carried out to improve solar energy system efficiency. Dang *et al.* (2019) estimated a thermosyphon solar water heater's thermal efficiency based on the storage tank heat exchanger's traditional and twisted style. From the result, the system's collector efficiency based on the "twisted heat exchanger" configuration was about 12.8% greater than that of the "conventional round heat exchanger." Rejeb *et al.* (2020) developed and tested a new PVT collector's performance, designed using a low emissivity coating with an optical anti-reflective content. A multi-physics model

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was developed to evaluate the electrical and thermal performance of the new design. The results showed a higher electrical and thermal efficiency of 15.4% and 73% respectively for the proposed PVT, compared with the basic PVT which has 13.7% and 58% electrical and thermal efficiencies respectively. Shariah and Shialabi (2013) have used the TRNSYS simulation program to optimise a solar flat plate water heater under Jordan's environment. The results indicate that the solar fraction of the energy system can be improved by 10 to 25% if the components are correctly measured and parameters are optimally selected.

Sohani *et al.* (2020) through outdoor experiment under Iran's weather condition evaluated the conventional solar-still thermal performance based on eight different system configurations. In the analysis of their result, the authors found that employing both the side mirror and sun-tracking on a solar-still operated in a passive mode increase the daily water production by about 43.1% relative to the conventional solar still. Moreover, Hoseinzadeh *et al.* (2017) discovered that employing the flat plate solar collectors for cooling and heating of traditional households in Northern Iran is not currently competitive with the conventional energy system. Nezhade, (2017) found that high input of auxiliary heating in a solar water heater design for an aviculture unit, would cause the inlet and outlet of the heat exchanger to be equal for a much longer time and thus reduce the heat exchanger efficiency. Hoseinzadeh *et al.* (2020) used the HOMER software to find the optimal size of the solar photovoltaic required to be combined with a 65kW capacity hydroelectric power system in order to improve the system's year-round capacity in meeting the power requirement a remote village of Mashhad Sarrood far from the grid in Iran.

Several literature works have reported attempts to redirect fluid flow over the heated surface to enhance the heat transfer between the surface and the fluid. A recent study (Menni, Azzi and Chamkha, 2019) showed that the heat transfer coefficient on a heated surface substantially influences the heat transfer between the heated surface and the fluid. Ahmadi *et al.* (2018) reviewed the current solar energy technologies to find the technology that best matches power production. The review concluded that the direct method of converting solar energy to power employing the PV module is most appropriate in scale power production. In contrast, employing a solar concentrator to generate steam, which is converted to power, is beneficial with a higher return in large-scale power production. Fawaz, Badawy, Abd Rabbo, & Elfeky (2018) investigated employing numerical simulation, the V-baffles' effect with 45 degrees angle of attack mounted with an in-line arrangement in a square channel with a fully developed turbulent fluid. Their findings showed that an in-line V-baffle design in fluid channels leads to more uniform mixing with high thermal enhancement, especially for flows at Reynolds numbers under 5000. In a recent study, Ahmadi *et al.* (2020) employed machine learning techniques to predict the thermal energy production and collector efficiency of a PVT collector. The statistical model prediction of the PVT collector efficiency shows a high confidence level (R^2) of 0.986 and minimum Mean Squared Error (MSE) of 0.007.

Zulkifile *et al.* (2018) found that the thermal efficiency (71.18%) of a Fresnel covered air heater is higher than that of a glass-covered air heater (54.10 %). Furthermore, the authors' outdoor test under the Bangi (Malaysia) weather revealed that the Fresnel covered V-groove air heater delivered hot air at 38.39°C. In contrast, the glass-covered V-groove air heater delivered hot air at 35.8 °C. Hossain *et al.* (2016) modified the serpentine flow pattern, to a two-side parallel serpentine flow pattern to increase the collector's thermal efficiency. The performance of the collector was experimentally tested under an outdoor condition in June and July. The result shows that the 2-sides parallel serpentine with bends at 90° has a peak collector efficiency of 81.26% and 80.10% for June and July. Deng *et al.* (2019) submitted based on China's economic scenario that the use of anti-freeze fluid solution in the indirect-loop employing refrigerant in the primary heating circuit of the flat plate solar collector for extremely low-temperature region potentially increases the system's cost by about 30% compared to an direct-loop system of heating water. To avoid structural failure, in the direct-loop solar water heating system due to freezing, the authors developed a new flat plate collector that is ice-immuned using a flexible and compressible silicone tube. Besides, the system's primary heating circuit operates in an open loop eliminating the need for a heat exchanger. The outdoor experimental test results showed that the header riser type collector's performance based on the flexible and compressible tubing performs slightly better than the serpentine tube panel. However, the serpentine tube panel's optical loss is lower by about 3.4–3.9% than that of the header riser type.

In addition to the structural improvement in the flat plate collector design, many attempts have been made to improve the collector's efficiency by using different work fluids (Kiliç, Menlik and Sözen, 2018; Eltaweel, Abdel-Rehim and Hussien, 2020). The serpentine solar collector's basic structure comprises a single line copper tubing embedded on an absorber plate in a serpentine fashion inside a casing cover at the top utilising glass. Many studies have suggested different structural modifications to the copper tubing with excellent thermal efficiency improvement compared to the primary serpentine tubing (Rosli *et al.*, 2014).

For most flat plate collector design, the collector is designed with a single fluid passage to deliver the desired hot water through one outlet. This type of collector design is mostly suitable for hot water application with a fixed desired temperature. However, in health centres, there is variation in the desired hot water's temperature based on application. For example, hot water requirements for equipment sterilisation are usually needed at a temperature of 55 to 60°C (Backer, 1996; Costa and Bracco, 2009). For laundry purposes, hot water temperatures are requested at 45 to 54°C (Honisch, Stammering and Bockmühl, 2014). According to Murphy (1993), and Lima *et al.* (2015), the hot water for bathing (postnatal service) is usually delivered at a temperature of around 37 to 45°C.

Therefore, this research proposes a serpentine collector configuration with three separate fluid passages to deliver hot water at three different temperatures to meet hot water demand for sterilisation at 60°C, laundry at 54°C and bathing purpose at 43°C for application in

small health centres. Therefore, the goal is to compare the benefit of the proposed configuration over the conventional flat plate collector used in most studies. The remaining sections are structured as follows: Section 2 discusses the proposed system architecture, system sizing and performance evaluation methodology. Section 3 explains the results obtained, while section 4 summarises the finding and conclusion of this study

2. Materials and Methods

2.1 Description of collector and system

The conventional serpentine solar collector is modified to have three different in-line copper pipes fluid passages, as shown in Figure 1. The hot water requirement of 150 L/day at a temperature of 54°C for laundry in ‘tank 1’ is conveyed by the first pump (P1) through the black passageway to reach the collector through the first inlet. Similarly, the water requirement of 88 L/day at 60°C for sterilisation and postnatal services of 113 L/day at 43°C in tank 2 and 3 enter the collector through the second (blue passages) and third (red passages) inlets respectively. Since water from the different tanks is conveyed via different fluid passages in the collector and each travelling the different copper tubing length, the water exits the collector at different temperatures. The tanks are sized based on each application’s hot water demand, as shown in Table 1. Furthermore, the power needed to operate the constant flow pumps is obtained from a 200 Watts PV module installed as part of the system. The system’s

analysis is based on 80 Litre per bed hot water specifications as recommended by (Fuentes, Arce and Salom, 2018) for three applications: laundry, sterilisation and postnatal services for a four-bed outpatient rural clinic located in Bauchi Nigeria.

2.2 Methodology for collector sizing

The sensible heat consideration in system design is calculated as the heat required to increase the temperature to meet the desired load temperature. For instance, if the rate of hot water demand is \dot{m}_L , in kg/hr then the heat Q_s required per day to increase the mains water temperature (T_{mains}) to the desired load temperature (TL) is expressed in Eq. (1) (Hoseinzadeh and Azadi, 2017).;

$$Q_s = \int_1^{24} \dot{m}_L C_p (T_L - T_{mains}) \quad (1)$$

Losses from the storage tanks may be significant and should be considered part of the total system load. The rate of tank losses (Q_{stL}) is estimated using the tank loss coefficient-area product $(UA)_{st}$ (mostly specified in the manufactures datasheet and the temperature difference between the tank water temperature T_{st} and the ambient temperature T_a surrounding the tank. Similarly, the total loss per day is calculated using Eq (2) (Govind and Shireesh, 2006).

$$Q_{stL} = \int_1^{24} (UA)_{st} (T_{st} - T_a) dt \quad (2)$$

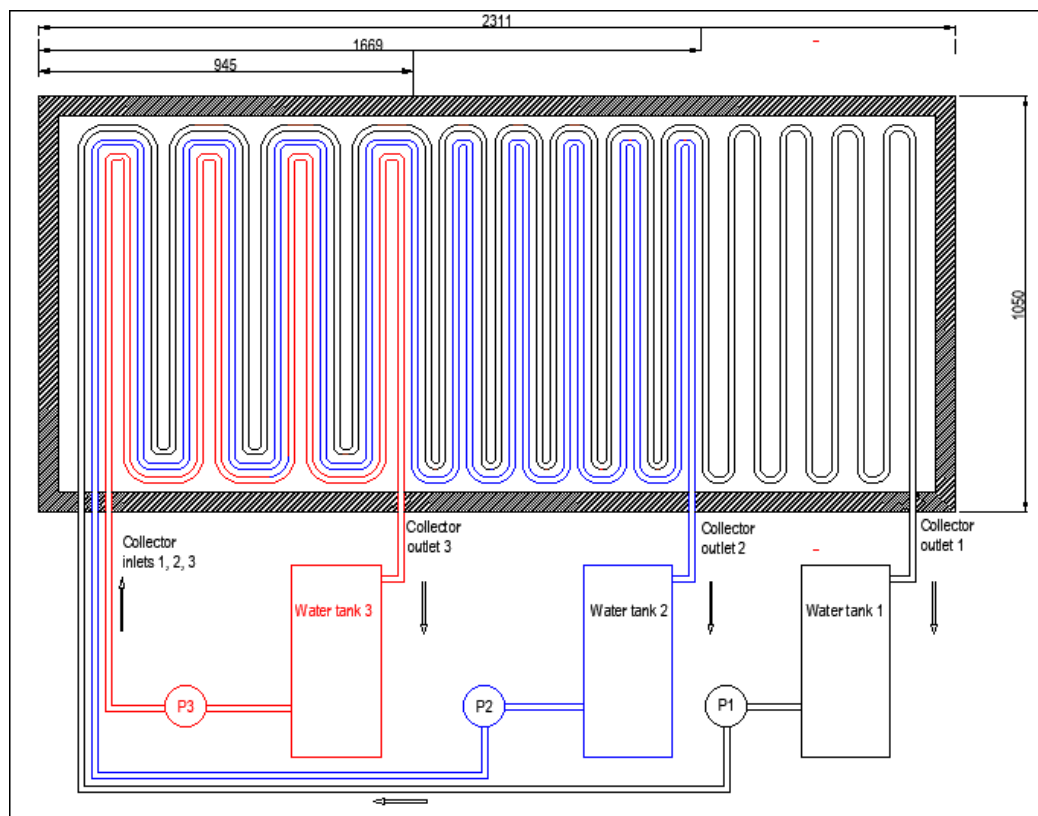


Fig 1. Schematic of the tri-inlet serpentine solar water heating system

For good performance, the solar collector must be sized to meet both the sensible heat requirement and the tank loss which is expressed by Eq (3);

$$Q_L = Q_s + Q_{stL} \quad (3)$$

The heat needed to raise the temperature of water required at a flow rate (\dot{m}) in kg/hr of the supply mains temperature (T_{mains}) to the load desire temperature for laundry, postnatal and sterilisation applications is calculated using Eq(4) to (6) respectively.

$$Q_l = \int_1^{24} (\dot{m}C_p(T_l - T_{main}) + Q_{stL})dt \quad (4)$$

$$Q_p = \int_1^{24} (\dot{m}C_p(T_p - T_{main}) + Q_{stp})dt \quad (5)$$

$$Q_s = \int_1^{24} (\dot{m}C_p(T_s - T_{main}) + Q_{sts})dt \quad (6)$$

where C_p is the specific heat capacity of water in kJ/kg.K. Q_l , Q_p , and Q_s are the average daily thermal energy demand for laundry, postnatal and sterilisation services obtained by integrating the hourly hot water demands. T_l , T_p and T_s are the desired hot water temperature for the laundry, postnatal and sterilisation services. The second term in Eqs. (4) to (6) represents the tank losses of the respective hot water storage tanks for the various applications.

Furthermore, from each application's daily thermal energy requirement values, the collector area requirement is approximated for each application based on Eq. (7) to Eq (9).

$$A_l = \frac{Q_l}{LF \times \int_1^{24} (I_T)dt} \quad (7)$$

$$A_p = \frac{Q_p}{LF \times \int_1^{24} (I_T)dt} \quad (8)$$

$$A_s = \frac{Q_s}{LF \times \int_1^{24} (I_T)dt} \quad (9)$$

where LF (0.56) is the hourly utilizability factor of the hourly available irradiance (I_T) obtained from the study location's solar radiation analysis based on formulations, as suggested by Duffie and Beckman (2013).

Notably, estimating each application's collector area is not for the three collectors to be constructed separately. The goal is to have an idea of the highest collector area needed per application. Consequently, the smaller areas are embedded in the biggest area to form a single collector, as shown in Figure 1. The size of each collector area estimated based on Eqs (7) to (9) determines the length water passages' tubing, as shown in Figure (1). The application with the highest estimated collector area has the most extended collector tubing, as indicated by the black colour tubing in Figure 1. Accordingly, the length of the fluid passage for each application is per the collector area.

2.3 Modelling and Performance simulation

To simulate the proposed solar water heating system's annual performance, the entire energy system model was formulated in the TRNSYS simulation studio, as shown in Figure 2. In the simulation studio, each component of the entire system is represented by a black-box model (called TYPE) of the component found in the component library of the studio. Besides, each TYPE of the system's component models the component behaviour based on mathematical equations described in the TRNSYS documentation.

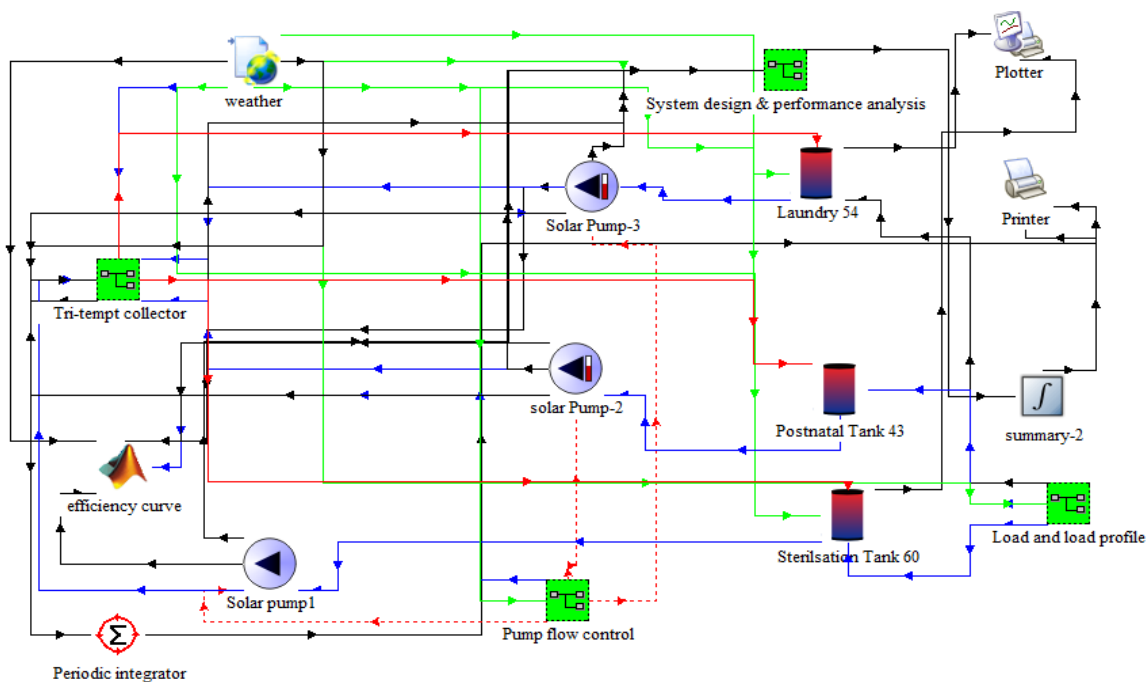


Fig 2. TRNSYS model of the proposed energy system developed

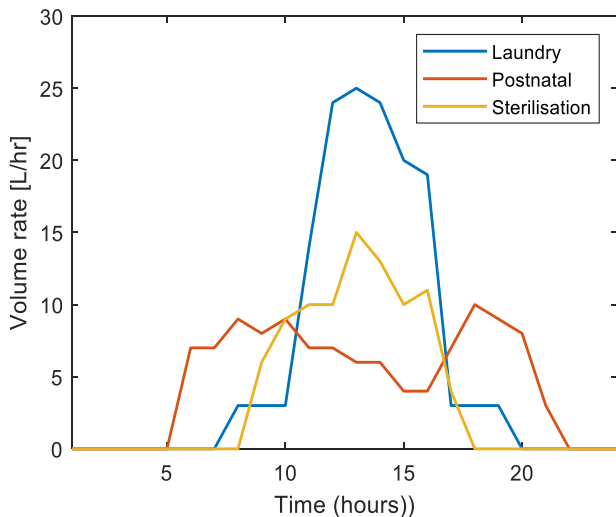


Fig 3. Hot water demand profile for the various services

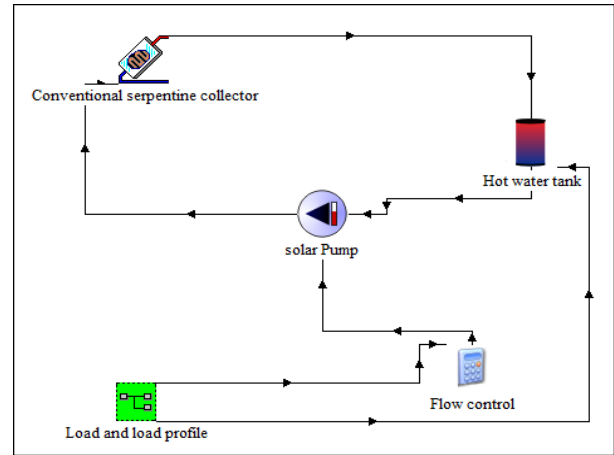


Fig 4. Model of the conventional serpentine water heating developed using TRNSYS

Accordingly, each TYPE takes input from other components and outputs the component performance based on its inputs. Notably, the components (TYPES) of the entire energy system must be connected in a manner that depicts the correct interactions between each system component. Furthermore, to customise any component's input based on the designers' choice, the equation block is used. In this block, the component control operation can be formulated based on some input equations. For instance, the "equation blocks" in Figure 2 shown by the green box represent the proposed pump control and the system's performance analysis, as indicated by each block's name. In this study, the pump is controlled to run at a constant flow rate of 0.02 kg/s only when solar radiation is available.

Moreover, the general utility forcing function called TYPE 14 is used to set a time-dependent hot water demand profile, as depicted in Figure 2 with the green box. Two load profiles are adopted. The first with a peak water demand around midday usually for sterilisation and laundry operation and the second with early and late evening peak for the postnatal services as shown in Figure 3. According to a study conducted by Bujak, these profiles are typical load profiles of health centres (Bujak, 2010). After each part of the entire system's parameters are defined based on careful engineering design principles, as shown in Table 1, the system's annual performance is simulated under the actual load and outdoor weather conditions of the health centre located in Bauchi, Nigeria.

The system's efficiency was compared with the typical serpentine solar heating system, as seen in Figure 4. The typical serpentine has the same dimensions and parameters as the proposed system. The comparison aims to benchmark the proposed solar water heating system with the typical serpentine configuration. In this case, this traditional serpentine solar heating system is utilised to meet the thermal demand of the same health centre based on single hot water tank with a volume equal to the total volume of hot water demand for the three applications as in generality of much-published work with a single centralised storage tank was used for this collective application (Lima *et al.*, 2015; Fertahi *et al.*, 2019; Li *et al.*, 2020).

Consequently, the monthly average daily system performance is evaluated based on the sets of equations described in section 2.4. The results of the annual performance assessment are discussed in the next sections

2.4 System Performance measurement and analysis

In solar systems design, the weather conditions strongly influence the size of the system. However, the weather condition of any place is highly random and unpredictable. Therefore, proper sizing of the solar system is a complicated and tricky task (Kalogirou, 2009). The numerical simulation using TRNSYS is an approach used to evaluate the solar system's long term (annual) performance based on the preliminary design parameters (Diez *et al.*, 2019). With this approach, it is possible to visualise the hourly and even daily performance throughout the year. Therefore, it will be possible to adjust design parameters until a reliable performance is reached. To predict the thermal characteristic in a steady-state of the flat plate collector, the Hottel-Whillier-Bliss (HWB) mathematical models and energy balance equations expressed in Eq.(10) models the collector component. The rate of useful energy gain of the solar collector at a given moment is the positive difference between the energy absorbed by the plate and the energy lost by the collector to the environment as described by Eq. (10) (Diez *et al.*, 2019).

$$\dot{Q}_u = F_R [S - U_L (T_i - T_a)]^+ \quad (10)$$

Where S, U_L, T_i and T_a are the energy absorbed by the absorber plate, the collector overall heat loss coefficient, circulating fluid collector inlet temperature and the temperature of the surrounding where the collector is placed respectively. The plus superscript indicates that only positive values of the square bracket terms are to be used. The Hottel-Whillier equation defines the efficiency of a solar collector under a steady radiant energy per unit area (I_T) falling on the collector surface with fluid flowing at a steady fluid flow rate, and constant wind speed and ambient temperature, as expressed in Eqn. (11) (Braun *et al.* 2020)

$$\eta_{coll} = \frac{Q_u}{I_{TA_c}} \quad (11)$$

The collector efficiency is calculated as the ratio of the total useful energy from the collector to the total solar radiation (I_{TA_c}) received on the collector surface. The efficiency is estimated from Eq. (12)

$$\eta_{coll} = \frac{Q_{u1} + Q_{u2} + Q_{u3}}{I_{TA_c}} \quad (12)$$

where Q_{u1} , Q_{u2} and Q_{u3} are the useful energy of the proposed collector from outlet 1, 2 and 3 respectively and A_c is the total collector area.

To evaluate the overall system performance, the solar fraction SF is a better performance indicator than the collector efficiency and heat removal factor. It assesses the entire system's overall efficiency rather than a component. Beausoleil-Morrison *et al.* (2019) expressed solar fraction as the fraction of the actual hot water demand met by the solar system to the total system load.

$$SF = \frac{\text{Actual load met by solar system}}{\text{Total system load}} = 1 - \frac{Q_{Aux}}{Q_L} \quad (13)$$

where, Q_{Aux} is the energy supplemented by another system component to provide for the shortfall needed to

meet design load completely. This energy could include supplementary thermal energy by electric or gas boiler. The average daily auxiliary energy is found from the positive value of Eq. (14). When Eq (14) results in negative value during the simulation, the negative values are taken as the system's excess thermal energy.

$$Q_{aux} = \left[\int_1^{24} \dot{m}_L C_p (T_L - T_{mains}) - \int_1^{24} \dot{m}_L C_p (T_d - T_{mains}) \right]^+ \quad (14)$$

T_d and T_{mains} are the hot water temperatures delivered by the system and the mains water temperature. Another performance indicator that does not consider whether the collector's energy matches demand is system efficiency. Using this evaluator gives an idea of how well the system converts the total incident energy to hot water without concern for its usefulness. The system efficiency is defined as the ratio of the heat that changes the mains water temperature (T_{mains}) to the temperature at which water is delivered (T_{LDT}) by the system load to the total energy received on the collector surface (H_{TA_c}) as expressed in Eqn (15) (Ayompe and Duffy, 2013);

$$\eta_s = \frac{\dot{m}_L C_p (T_{LDT} - T_{mains})}{H_{TA_c}} \quad (15)$$

Table 1
 The design parameters and components sizes of the proposed solar hot water heating system

Component	TRNSY TYPE	Parameter	Value	unit	remark
1 solar collector	565	Absorber plate thickness	3.18	mm	
		Conductivity of absorber material	220	W/m.K	Absorber plate made from Al.
		Serpentine Spacing	0.1	m	
		Serpentine Length	1.0	m	
		Inner tube diameter	0.01	m	
		Outer tube diameter	0.012	m	
		Absorptance absorber plate	0.9	-	
		Emissivity of the Absorber Plate	0.95	-	Emissivity of matt black paint
		Number of glass cover	1.0	-	
		Collector tilt angle	11.0	Deg	equal to the latitude of the location
2 Water storage tank	158	Tank Volume (Laundry)	0.15	m ³	Equal to the daily volume of hot water demand
		Tank height for all tanks	1.20		
		Tank Volume (post-natal)	0.113	m ³	Same reason as above
		Tank 3 (Sterilisation)	0.088	m ³	Same reason as above
3 solar pump	110	Rated flow rate	0.02	kg/s	As recommended in most studies
		Power consumption	64	watt	

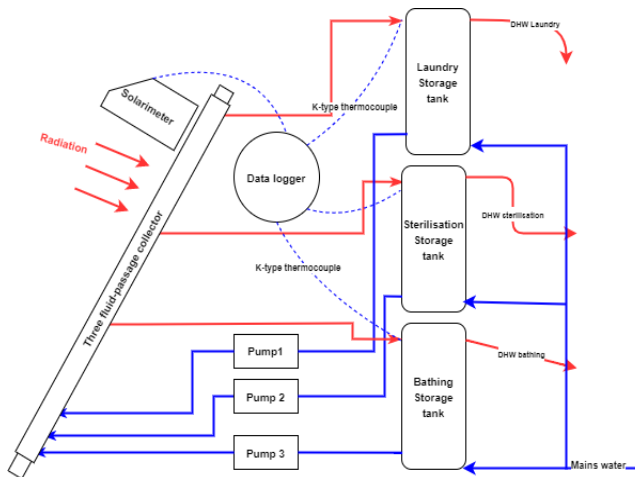


Fig 5. View of the outdoor experimental setup of the proposed 3-loop solar water heating system

2.5 Experimental validation of system model

To compare the system’s predicted performance, the simulated system was built. The outdoor performance of the system was experimentally measured at Abubakar Tafawa Balewa University Bauchi, Nigeria. Figure 5 shows the developed system and experimental setup used to measure the system’s outdoor performance. The water temperature in the storage tank was the selected parameter for validation. This parameter is crucial to both the designer and the end-user (Yanto *et al.*, 2017).

The performance was measured one day in January and August. These months are selected because they represent months with good solar and poor solar radiation, respectively. Each day experiment was started from 8:00 hours to 18:00 hours. During the experiment, the three-tank outlet and inlet temperatures were measured at an interval of one hour using, a K-type thermocouple wire connected to a digital reader. The flow rate through the collector was taken as the pump’s flow rate since the pump is operated at a constant flow rate of 72 kg/hr during the test period. The solar irradiance received on the collector’s surface was also measured using the digital pyrometer with an accuracy of +/- 50 watts. The hourly measurement of the temperatures obtained during the experiment was recorded for laundry, sterilisation and postnatal services. These results were analysed using the statistical tool to determine the validity of the model formulated using TRNSYS. The coefficient of variation of the root-mean-square error, Cv(RMSE) and Nash-Sutcliffe coefficient of efficiency (NSE) given by Eqn. (16) and (17) (Yanto *et al.*, 2017) (Teixeira *et al.*, 2020) were adopted to compare to measure the relative error between the predicted temperature and measured temperature. The confidence level of the model was assessed based on NSE Eqn. (19). ;

$$Cv(RMSE) = \sqrt{\frac{\sum_{i=1}^n (X_{sim,i} - X_{expt,i})^2}{n}} \times \frac{100}{\bar{X}_{expt,i}} \quad (16)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (X_{expt,i} - X_{sim,i})^2}{\sum_{i=1}^n (X_{expt,i} - \bar{X}_{expt,i})^2} \quad (17)$$

where X_{sim} is the simulated parameter, X_{expt} is the measured parameter and \bar{X}_{expt} is the experimental mean of the measured variable.

3. Results and Discussions

3.1 Analysis of system load

The weather condition, which significantly influences solar system design varies randomly with time for every location (Brownson, 2014). As a result, solar energy system performance equally, varies significantly with time and locations. Therefore, assessing the solar energy system’s performance on a monthly average daily basis is considered a reasonable approximation and fair assessment of system performance. Figure 6 shows the monthly average daily thermal load demand for each application. The thermal demand for laundry, sterilisation, and postnatal services are significantly different due to the difference in volume and temperature required for each hot water application. Notably, while the volume (88 L) of hot water demand for sterilisation is lower than that needed for postnatal services, the thermal demand for sterilisation is approximately 20% higher than that required for postnatal services. This difference again shows that the temperature at which the hot water is required is crucial in determining the energy requirement. In this case, a difference of about 20% signifies a potential reduction of the collector’s total thermal energy production to meet hot water demand if separate hot water tanks are employed.

The implication of employing a single hot water tank in the solar system for hot water demand at different temperature and volume is that the water is mixed. Consequently, to satisfactorily meet hot water demand at 43°C, 54°C and 60°C as in this study, the water must be heated to a temperature of 60°C. In this case, the collector size required will be much higher than necessary. Besides, for hot water required at different temperatures, meeting the demand at a higher temperature may result in excess thermal energy dumped.

In this case, the hot water requirement for sterilisation is 88 litres. Postnatal and laundry services require 113 litres and 150 litres, respectively. The overall demand in this health centre for hot water, therefore, stands at 351 litres. As mentioned earlier, the demands for the separate services are separated into three different tanks. Therefore, based on the established equations in section 2 of this study, the thermal energy required to increase each tank’s temperature to the desired temperature is calculated and summed to obtain the total thermal energy demand. the total energy is compared to that required if the hot water demand for each application is combined in a single tank and then heated to the maximum temperature demand of 60°C. Figure 7 compares the total energy demand for separate hot water tanks and the single hot water tank. It was observed that the total thermal energy demand for heating the total volume of hot water to 60°C in a single tank is significantly higher by about 27% than that required to meet the demand for the various applications if the hot water demand is separated and meet separately. The drawback of sizing the solar water heating system to meet hot water demand based on the single storage tank, as demonstrated in this study is the production of excess thermal energy.

This excess energy is mostly dumped since it cannot be stored.

3.2 Collector efficiency and characterisation

The system temperature behaviour recorded during the outdoor experiment on a clear day is processed to characterise the proposed “three fluid-passage” serpentine collector, as shown in Figure 8. From the equation of the line of best fit, the slope of the efficiency curve was found to be $6.1 \text{ W/m}^2\text{K}$. The slope of the efficiency curve is equal to the collector heat removal-loss efficient product ($F_R U_L$) and the intercept of the line on the efficiency axis is the heat removal factor-transmittance absorptance product ($F_R \tau \alpha$) equal to 0.71. The collector’s efficiency in this study is zero at a temperature difference of 0.12 and similarly zero at a temperature difference of 0.15 the review conducted by Akram (Akram *et al.*, 2020).

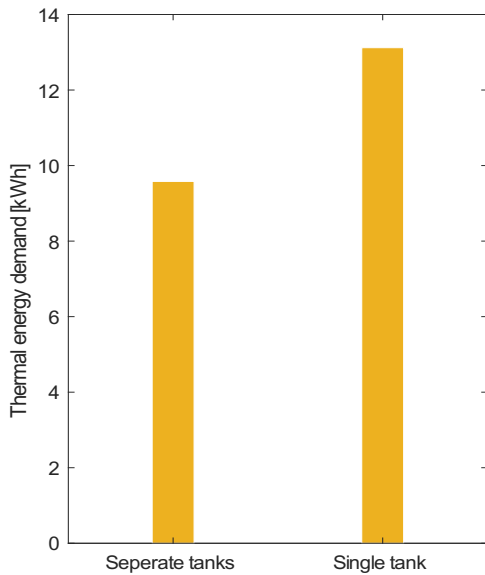


Fig 7. Total a hot water demand for separated tanks and single tank.

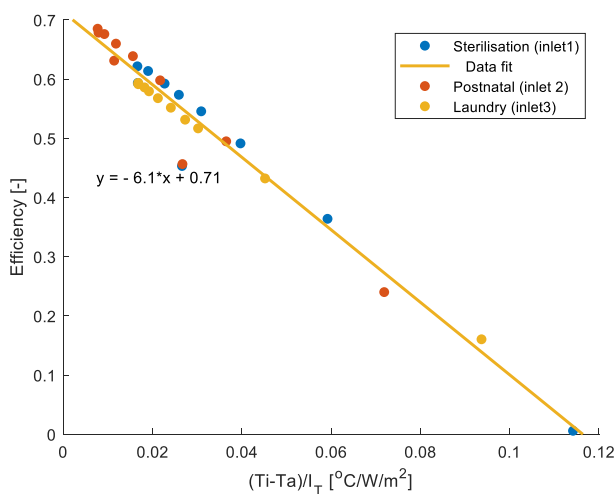


Fig 8. Efficiency curve of the proposed collector.

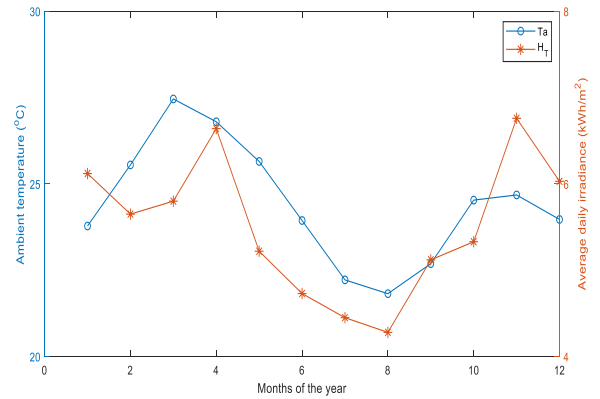


Fig 10. Monthly average daily solar irradiance and ambient temperature of Bauchi, Nigeria

Similarly, Figures 9 and 10 compare the proposed collector’s simulated collector efficiency to the conventional serpentine collector based on the same design and operational parameters on a clear sky day and cloudy sky day, respectively. From both figures, it is seen that for both sunny and cloudy days, the proposed collector configuration shows significantly higher collector efficiency than the conventional collector. This trend is due to the fact that the water coming into the collector is entering a low temperature since, for postnatal applications, the water is recirculated in the collector at a lower temperature (43°C).

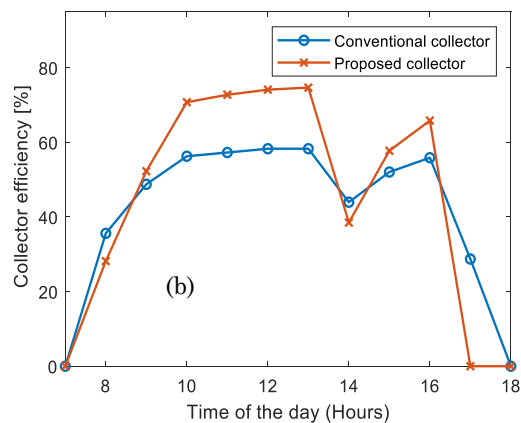
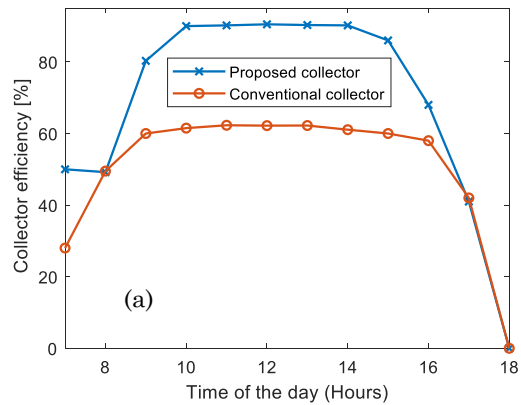


Fig 9. Collector efficiency of conventional and proposed on (a) cloudy day and (b) cloudy day

Hence, in this way, there is better extraction of heat by the circulated water compare to the single inlet collector operated base on a single hot water storage tank. Thus, the energy conversion rate to useful thermal energy in this study is about 30% and 20% higher in the proposed collector than the conventional serpentine collector on both sunny and cloudy days respectively as observed in Figures 9.

3.3 Monthly average temperature of hot water delivered

Comparing the monthly averaged daily hot water delivered for the three applications, Figure 9 shows that the hot water temperature delivered by the system for postnatal service is above the required temperature in most of the months. As seen in Figure 9, these performances reflect the solar radiation availability in each month. For this study, solar radiation is higher from January to May and September to December, as shown in Figure 10. June to August shows a lower level of solar radiation; hence system performance is lower in these months, as seen in Figures 9. Significantly, the auxiliary energy requirement is divided when loads are separated, allowing for just the energy required in each application to be supplied.

3.4 System thermal performance analysis

The solar fraction, which is the portion of the load met using a solar energy system, is a critical indicator to assess the solar system's overall performance. The solar fraction is a performance matrix that measures the entire system performance rather than the component performance. It is, in other words, it a performance matrix that reveals the system capacity to meet the hot water demand at the desired temperature. Figure 12 compares the system's monthly average daily solar fraction based on the tri-inlet/outlet collector and the conventional serpentine collector. Overall, the system's solar fraction based on the proposed collector configuration and system architecture is observed to be higher in all months than that based on the conventional serpentine collector and system architecture. As seen from Figure 13 the average daily useful energy (solar fraction) based on the proposed designed is about 83.5% indicating an improvement of about 11.6% in a solar fraction when compared to the convention system architecture which has a solar fraction of 71.9%

A detailed thermal assessment of the three tanks' hot water for the different applications indicates that the hot water is delivered at a higher temperature at sometimes, as seen in Figures 11. This elevated temperature consequently produces the excess thermal energy. Unfortunately, excess thermal energy in a solar water heating system that is not used immediately has no economic value. Therefore, oversizing to produce excess thermal energy has no economic value. While excess thermal energy of about 3.6% and 18.25% was supplied by both the proposed system and conventional system architecture, approximately 28% and 16% of auxiliary energy still must be supplied to meet all thermal needs reliability. Hence, suggesting that the excess thermal energy is merely due to load mismatch.

Overall, the proposed collector configuration and system architecture have shown higher solar fraction

capacity, reducing the extra needed energy by about 12%. This extra energy reduction has further shown that the system's carbon dioxide mitigation impact is further enhanced by the proposed system designed and collector configuration. Finally, a solar fraction of 67% for the month with the worst solar radiation as shown in Figure 12 shows that the collector's size is within the limit, as recommended by the National Renewable Laboratory (NREL) guideline for the design of solar water heating system (National Renewable Laboratory NREL, 2015).

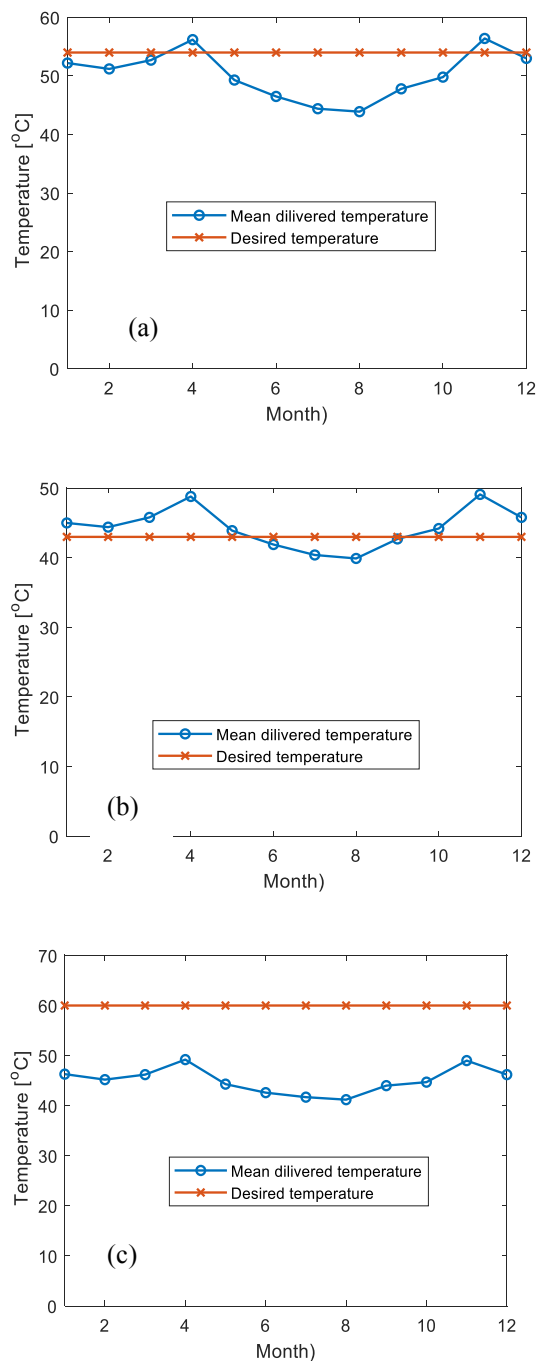


Fig 11. Monthly average water temperature delivered for (a) laundry (b) postnatal (c) sterilisation services, based on the proposed collector

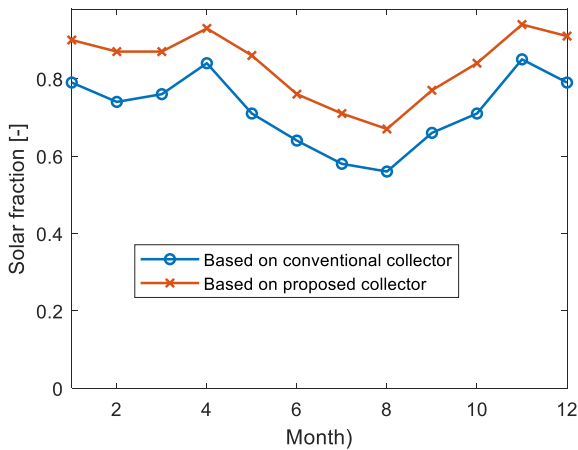


Fig 12. Solar system fraction based on the conventional and the proposed collector

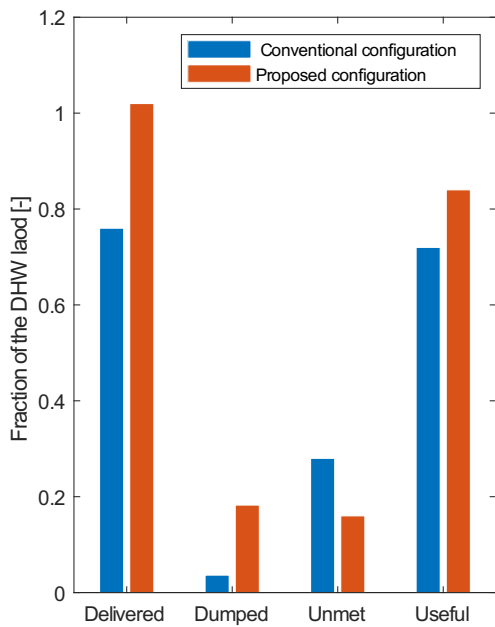


Fig 13. Performance of the proposed system in comparison to the typical serpentine system

3.5 Experimental validation of simulated results

Figures 14 and 18 compare the simulated tank outlet temperature with the measure tank outlet temperature for postnatal (a) and laundry (b) on the 4th of January and August. January represents the system performance on the day with a high level of solar radiation and clear sky. Similarly, August stands for the system’s performance daily with low radiation and cloudy sky level. Table 2 shows the Nash-Sutcliffe coefficient of efficiency (NSE) between the measured and the predicted tank outlet temperature. NSE is a matrix used to evaluate how close, the formulated model represents the entire system. It is observed that the measured temperatures in all the tanks show close agreement with the simulated tank outlet temperatures. As observed from Table 2, a lower

CV(RMSE) value does not imply better agreement of measured value to the simulated result. Particularly in August, the simulated laundry tank outlet temperature is observed to have a Cv(RMSE) value of 11.7%. However, it has a confidence level (NSE) of 77.6% compared to a Cv(RMSE) value of 8.56% with a lower NSE of 67.2 % as observed with the postnatal tank temperature in August.

Overall, the average percentage error Cv(RMSE) of 8.67% and confidence level NSE of 87.6.1% shown in Table 2 exceed the minimal accepted values of the plus or minus 30 % and 60% respectively (Teixeira *et al.*, 2020).

Table 2 Error analysis of measured and simulated system performance

Month	Service tank outlet temperature	Cv(RMSE)%	NSE[-]
Jan	Laundry	9.379	0.905
	Postnatal	5.184	0.969
	Sterilisation	11.89	0.917
Aug	Laundry	11.02	0.776
	Postnatal	8.56	0.671
	Sterilisation	6.466	0.952
	Sys. Aver	8.75	0.87

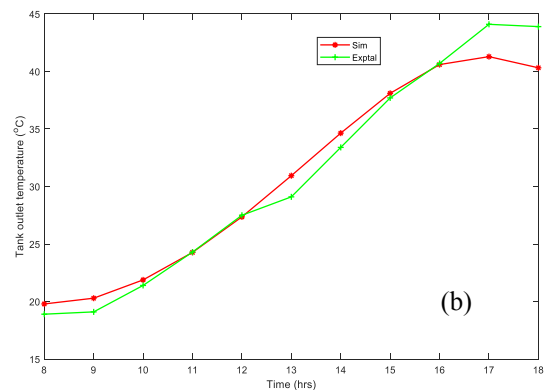
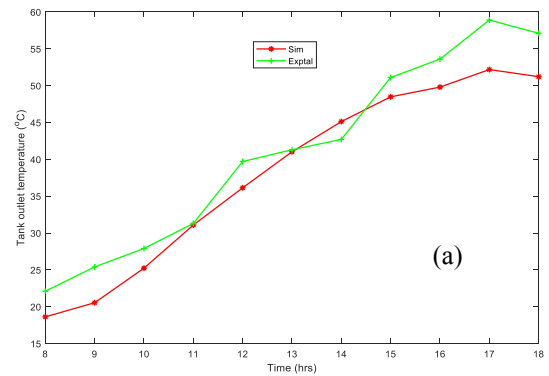


Fig 14. Comparison of simulated and measured tank outlet water temperature for (a) laundry and (b) Postnatal services tank on 4/01/2017

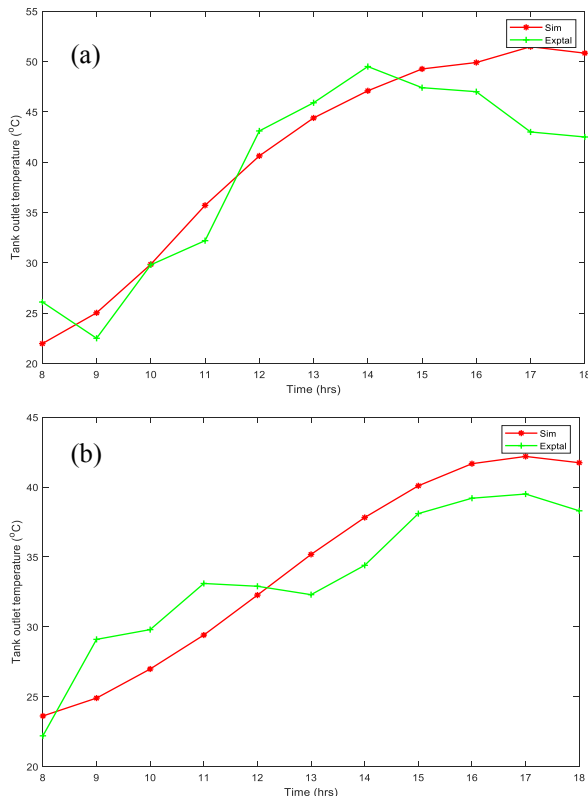


Fig 15. Comparison of simulated and measured tank outlet water temperature for (a) laundry and (b) Postnatal services tank on 4/08/2017

4. Conclusion

In this study, a novel serpentine, flat plate collector with three in-line copper fluid passages is proposed. The aim is to design a single collector that can supply hot water at different temperatures for sterilisation, laundry and postnatal services in small health centres. The study compares the system's performance based on the novel serpentine collector configuration to system performance based on the typical serpentine collector configuration to determine the proposed collector's advantage over the typical one. From the results of this study, the following conclusions are drawn. The three hospital hot water services' thermal requirement was significantly reduced by about 27% when the hot water demand for these services is provided employing three separate tanks. Moreover, the serpentine collector efficiency based on the proposed three in-line fluid passages is improved by about 20% relative to the conventional serpentine collector. Consequently, the average daily energy delivered to load based on the proposed collector configuration and system architecture is about 30% higher than that of the conventional serpentine system configuration.

Overall, the experimental system performance and the simulated system performance is in close agreement with an average percentage error Cv(RMSE) of 8.75% and confidence level NSE of about 87%. Therefore, the model formulated is a good representative of the existing system. The proposed serpentine collector configuration's thermal production is significantly higher than that of the conventional serpentine configuration. Hence, the proposed serpentine collector configuration is

recommended for hot water applications where demand is required at various temperatures and volumes. The second question is whether the study's proposed design is economically more effective than conventional serpentine collector design. Accordingly, in the future study, a feasibility study may be recommended to compare the proposed design with the traditional serpentine collector system.

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