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An Experimental Study on the Performance of a Stratified-Integrated Solar Water Heater

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Abstract

The problem of night cooling in solar water heaters has been considered in this study. The performance of a suggested Integrated Collector-Storage Solar Water Heater (ICSSWH) has been investigated. The proposed system is with a trapezoidal shape solar collector part, attached with an extended storage that is well thermally insulated. To monitor the temperature distribution of water inside the tank and to study the thermal performance of the system, a total of nine thermocouples have been placed inside the tank at vertical and inclined axes. Comparison of the system thermal performance in this project is made with a similar system studied by Ronald et al. (2019). The experimental results have shown that the ICSSWH system in current study has achieved a collection efficiency of 88% together with a retention efficiency of 25.5%, while the systems studied by Ronald et al. (2019) has achieved the highest retention efficiency of 47.8% together with a collection efficiency of 48%. Apart from that, comparison of system with different insulation thickness is made. System with 13mm insulation has shown a lower rate of temperature loss compared to system with 9mm insulation. Also, a heat retention efficiency of 24.6% and a heat loss coefficient of 1.03WK-1 is obtained after a cooling period of 18hours.

Introduction

Solar water heating systems are categorized into two major types which are active and passive systems [1]. Stratified-integrated solar water heaters, also known as integrated collector storage solar water heater (ICSSWH) falls in the category of passive systems which made up of a combination of solar collector as well as storage tank [2]. In late 18th century, ICSSWH first system has been demonstrated for the very first time at agricultural area in the Southwest of USA. As a result, enough hot water has been obtained for daily usage on the clear day [3]. The design of ICSSWH is simple, and to ensure the stratification effect to take place, the water tank must be designed at a position above the collector part. Also, ICSSWH system does not consist of moving components, pump for circulation as well as electronic controls [1]. Hence, ICSSWH system is considered as operational and maintenance cost free, where it only requires regular cleaning on the surface of glass cover. Therefore, the cost of ICSSWH is relatively low compared to active type of solar water heating systems.

The industry of ICSSWH system is developing and improving continuously to achieve the goal of delivering hot water efficiently to user with affordable range of cost that will eventually attract more interest in the global market. Factors such as size and shape of storage tank, types and orientation of absorber plate, method of insulation as well as the water temperature between inlet and outlet will cause the efficiency of ICSSWH to be affected. Hence, a variety of shapes and designs of ICSSWH systems is then proposed. Saleh (2012) tested that the water temperature as high as 60°C or even higher could be achieved in a rectangular tank type of ICSSWH system [4].

Flat plate ICSSWH system with low cost and simple design with effective collector area of 0.67m2 has been proposed by Taheri et al. (2013) [5]. Besides that, Devanarayanan and Kalidasa Murugavel (2014), have reported that ICSSWH system with compound parabolic concentrating (CPC) can be considered as a promising hot water heater for domestic use.

However, the drawback of all ICSSWH systems is the night cooling effect. Significant of heat is lost from the water to the surrounding during non-collecting period, especially at night-time. Therefore, numerous research and studies had been conducted previously by experts to come out with strategies in minimizing the rate of night cooling effect of ICSSWH systems.

The proposed strategies including the use of baffle plate. Ruth et al. (2018) reported that the use of baffle plate in ICSSWH system can aid in promoting the stratification effect [6]. In addition, Souliotis et al. (2011) studied the evacuated layer which is another form of thermal diode that is created between the absorber plate and water cavity [7]. Also, Chaabane et al. (2014) have conducted numerical study on the thermal performance of ICSSWH system mounted with two different type of phase change materials (PCM) and reported that myristic acid led to a better preservation of heat with a water almost 30°C higher after an operation of 18 hours [8].

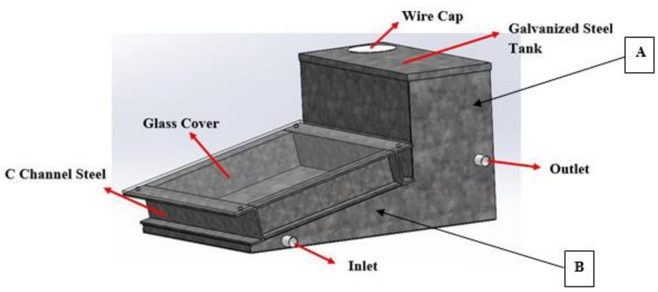

Figure 1 Overall structure of the ICSSWH system.

In this paper, an investigation on the thermal performance of a trapezoidal stratified-integrated solar water heater with extended storage has been conducted. Compartment A is the storage part while compartment B is the collector part of the system. The volume of both compartments is set to be equal to optimize the stratification effect. The stratification effect inside the tank will ensure the heat to flow from compartment B to compartment A during collecting period. Meanwhile, during non-collecting period, the heat from the water will lose to the surrounding from compartment B, and eventually the heat will still accumulate at compartment A to provide hot water for usage.

Research Methods

The solar water heater tank is made with a volume of 11.4L of galvanized steel having a thickness of 1mm and were painted black to increase the absorbability of the solar energy. Also, a 4mm thick tempered glass is mounted on the inclined surface of the tank.

The test starts off by filling up the tank with normal tap water knowing that the storage tank has been well insulated with double sided aluminum foil bubble film insulation with a thickness of 9mm. A total of nine calibrated K-type thermocouples (Nickel/Chromium) with an accuracy of ± 1°C are fixed in the positions shown in Figure 2, and then been installed inside the tank. A light projector of 1000W power has been used to represent the solar radiation. It has been set at an initial height of 30cm as shown in Figure 3. It can give an average solar simulated radiation of 1500W/m^2 that measured by a solar power meter TES-1333.

The measurements are taken at 30 minutes intervals for 6 hours of the collection period without any water withdrawal. The steps are then repeated to conduct another test with an average solar simulated radiation of 863W/m^2, 576 W/m^2 and 360 W/m^2, and it's by adjusting the height of the light projector.

Extra experiments have been conducted with a 13mm thickness insulation. The steps are repeated under the solar simulated radiation of 1500W/m^2.

In this test, the tank was kept with the hot water obtained during the shiny period. The system is then left to cool naturally at ambient temperature. The test is conducted under no water withdrawal conditions, for a total cooling period of 18 hours, which represents the time period of no or weak sunshine. The measurements are taken at 30 minutes intervals, and the readings are obtained by connecting the thermocouples to a digital multimeter. The water is then drained out from the tank after 18 hours, for the new experiments to be conducted.

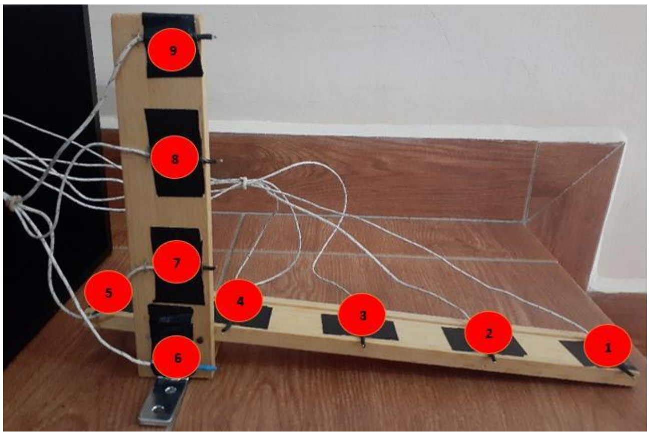

Figure 2 Position of thermocouples in vertical and inclined axis.

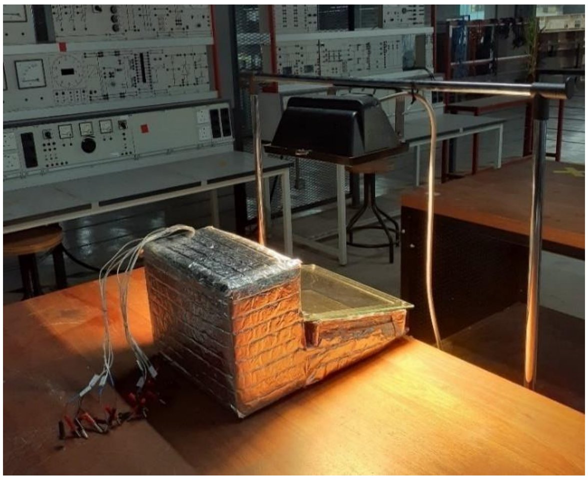

Figure 3 Indoor experimental test set up of ICSSWH.

Results and Discussion

The thermal performance of the system has been analyzed based on the experimental data obtained from the indoor solar energy collection and retention test. The heat loss coefficient of the system as well as the efficiency of collection and retention can be determined via calculation proposed by Smyth et al. (2017) and Ronald et al. (2019). The energy supplied over the collection period, $Q_{supplied}$ was determined by equation (1).

$$Q_{supplied} = I_{avg} \times A_{ap} \times \Delta t \qquad (1)$$

where I_{avg} is the constant average simulated solar radiation, A_{ap} represents the aperture area of the collector and Δt represents the period of collector illumination by the solar simulator. Meanwhile, $Q_{collected}$ which is the thermal energy collected can be obtained from the equation (2) shown

$$Q_{collected} = mc_p\ (T_{f,w} - T_{i,w}) \qquad (2)$$

where m represents the mass of water filled inside the stratified-integrated solar water tank, c_p represents the specific heat capacity of the water, $T_{f,w}$ represents the average final temperature of the water and $T_{i,w}$ represents the average starting temperature of the water. Hence, with the calculated value of $Q_{collected}$ and $Q_{supplied}$, the heat collection efficiency of the system is calculated by equation (3) shown,

$$\eta_{collection} = (Q_{collected} / Q_{supplied}) \times 100 \quad (3)$$

The heat collection period will lead to variation in heat collection efficiency. Hence, in this work, the heat collection efficiency during a collection period of 6 hours has been calculated. In addition, the heat retention efficiency, $\eta_{retention}$ of the system is determined by equation (4) shown,

$$\eta_{retention} = [(T_{final} - T_{ambient}) / (T_{initial,c} - T_{ambient})] \times 100 \quad (4)$$

where $T_{initial,c}$ represents the average temperature of water inside the tank at the beginning of cooling period, T_{final} represents the average temperature of water inside the tank when the cooling period ended, and $T_{ambient}$ represents the average ambient temperature during the entire cooling period.

In this work, the heat retention efficiency has been calculated for both 12 hours and 18 hours of cooling period. Lastly, the heat loss coefficient of the system (U), is obtained from the equation (5) shown,

$$U_{system} = (\rho c_p v_T / \Delta t) \ln [(T_{initial,c} - T_{ambient}) / (T_{final} - T_{ambient})] \quad (5)$$

where ρ and c are the density as well as the specific heat capacity of the water respectively. Also, the considered time interval of cooling period in seconds is represented by Δt.

After all experimental data collection, the thermal performance of the system is calculated and plotted into graphs for better understanding. As shown in Figure 4, the collection period as well as the cooling period can be observed clearly. Furthermore, the temperature loss during the cooling period is demonstrated in Figure 5.

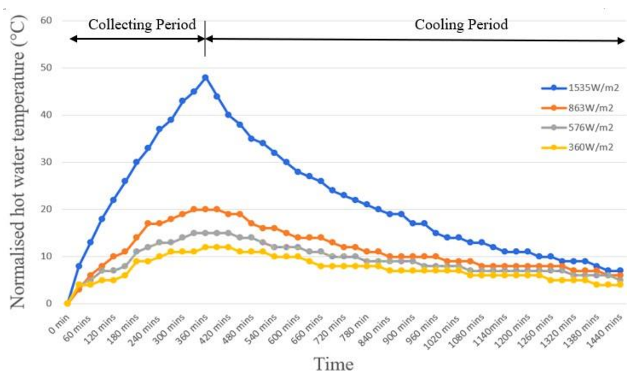

Figure 4 Heating and Cooling Performance for 9mm Insulation.

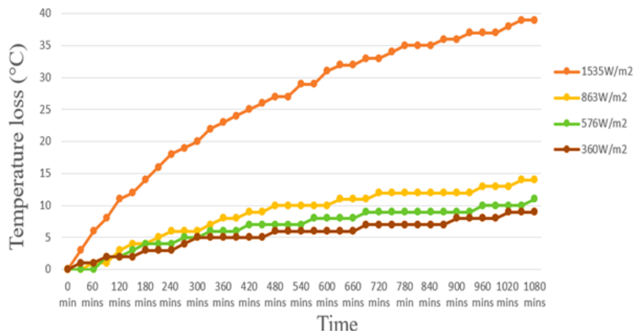

Figure 5 Temperature loss profile during the 18 hours cooling period.

By making comparison of thermal performance between the current system and the system studied by Ronald et al. (2019), it can be shown that the system in the current research has the highest heat collection efficiency of 88%, while the highest heat collection efficiency achieved by the system studied by Ronald et al. was 51.6%.

However, the system studied by Ronald et al. (2019), has achieved a heat retention efficiency of 47.8%, for a colling period of 18 hours, whether the current system has just achieved the heat retention efficiency of 25.5%. This may be due to the different material used in building the two systems. The comparison of heat collection efficiency and heat retention efficiency is shown in Figure 6 and Figure 7 respectively, as well as in Table 1.

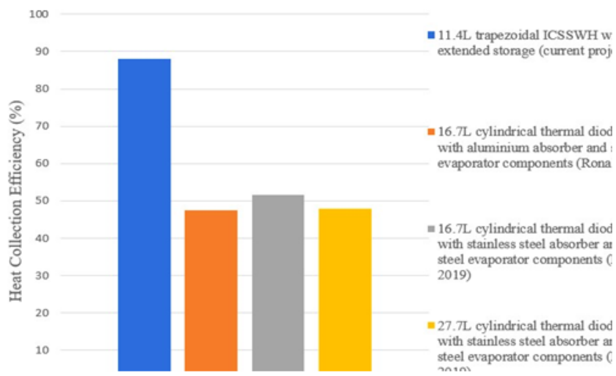

Figure 6 Comparison of heat collection efficiency between current ICSSWH system and the system studied by Ronald et al., 2019.

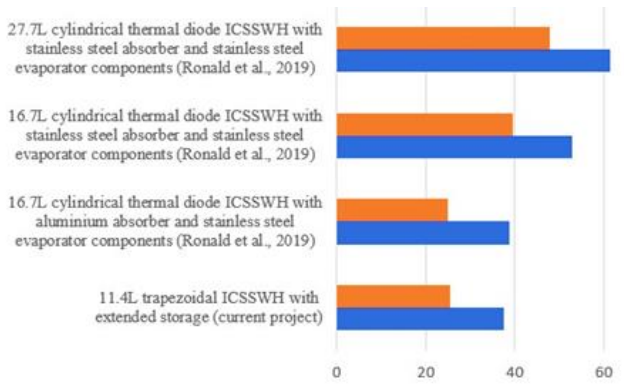

Figure 7 Comparison of heat retention efficiency between current ICSSWH system and the system studied by Ronald et al., 2019.

A comparison of thermal performance between system with 9mm insulation and the system with 13mm insulation is performed. Figure 8 and Table 2 are showing the comparison of thermal performance during the collection and cooling periods. From Figure 8, it can be shown that the system with 13mm thickness insulation is able to achieve a higher normalized water temperature of (50°C), which is 2°C higher than the system with 9mm thick insulation. Also, system with 13mm insulation can retain heat better with a normalized hot water temperature retention of 13°C compared to system with 9mm insulation that just have a normalized hot water temperature retention of 7°C. This is demonstrated in Figure 9 as well, where system with 13mm insulation has a lower temperature loss. Hence, a thicker insulation should be applied to achieve a better retention of heat inside the tank for a long period.

Table 1 Thermal characteristics comparison between current ICSSWH system and the system studied by Ronald et al., 2019.

System	11.4L trapezoidal ICSSWH with extended storage (current project)		16.7L cylindricalthermal diode ICSSWH with aluminium absorber and stainless steel evaporator components (Ronald et al., 2019)		16.7L cylindricalthermal diode ICSSWH with stainless steel absorber and stainless steel evaporator components (Ronald et al., 2019)		27.7L cylindricalthermal diode ICSSWH with stainless steel absorber and stainless steel evaporator components (Ronald et al., 2019)	
Heat collection efficiency for 6hours (%)	88		47.4		51.6		48	
Initial water temperature (°C)	48		54.7		59.4		49.4	
Duration of heatretention (hours)	12	18	12	18	12	18	12	18
Final water temperature (°C)	36	34	33.5	28.7	39.2	33.5	39.0	35.3
Average ambienttemperature (°C)	28.8	29.2	20.1	20.0	16.6	16.5	22.6	22.5
Heat retentionefficiency (%)	37.5	25.5	38.7	25.1	52.8	39.6	61.4	47.8
Heat loss coefficient (WK^{-1})	1.08	1.00	1.53	1.49	1.02	1.0	1.31	1.32

Conclusion

An experimental study on the thermal performance of a stratified-integrated solar water heater with extended storage has been conducted. The distribution of temperature inside the tank is monitored for 6 hours of collection period and for an 18 hours of cooling period. It has been found that the system in the current research has achieved an efficiency of 88%, while the highest heat collection efficiency achieved by the system studied by Ronald et al. was 51.6%.

However, the system studied by Ronald et al. (2019), has achieved a heat retention efficiency of 47.8%, for a colling period of 18 hours, whether the current system has just achieved the heat retention efficiency of 25.5%. This may be due to the different materials used in building the two systems.

It was found that the selection of material is crucial and have to be taken into consideration in order to design an ICSSWH system that is able to minimize the rate of heat loss especially during the non-collecting period. It can be also concluded that the thermal insulation thickness is playing an important role in minimizing heat loss and retaining heat for a longer period.

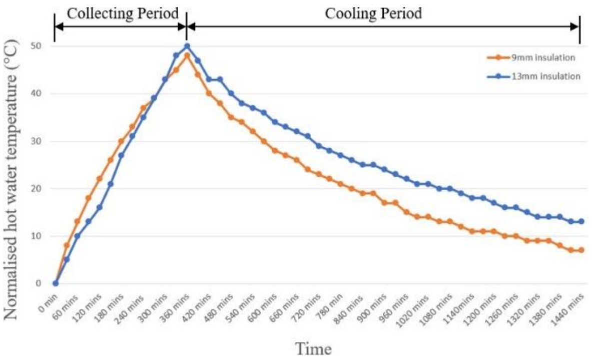

Figure 8 Comparison of performance between the two systems with 9mm and 13mm thermal insulations.

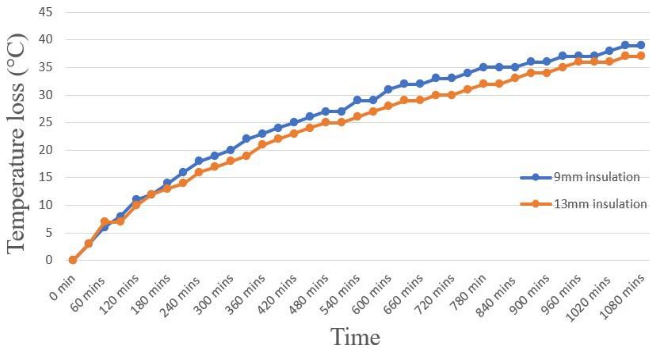

Figure 9 Comparison of temperature loss profile during the 18 hours cooling period between insulation with thickness of 9mm and 13mm.

Table 2 Characteristics of thermal retention during a 12 hours and 18 hours of cooling period.

	Insulation with thickness of 9mm								Insulation with thickness of 9mm	
Distance of light source from the glass cover	30cm		50cm		70cm		90cm		30cm	
Duration of heatretention (hours)	12	18	12	18	12	18	12	18	12	18
Initial water temperature (°C)	74		48		44		41		79	

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