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Effectiveness of capsules installation containing paraffin wax in a solar water heater

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Abstract
The encapsulation technique is one way to use latent heat storage material in a solar water heater tank. In this technique, several capsules may be arranged in the tank. In this study, the capsules were installed along the cross-section of the tank. There has been no discussion of which part of the capsule position has optimal heat energy with a capsule arrangement. Proper placement of the capsule arrangement can result in optimal thermal energy storage in the tank. This study aimed to investigate the effectiveness of installing capsules in a tank with different positions in terms of thermal energy storage. The study used an active solar water heater. The 24 capsules containing paraffin wax were arranged in a tank. The solar simulator was used as a heat source for the collector, and it was set at 1000 W/m^2. The flow rate of water was 2 liters/minute. During the charging process, the water and paraffin wax temperature was recorded. The temperature evolution of water and paraffin wax obtained were used to analyze the thermal energy content. The results showed that the average heating rate for water and paraffin wax was 0.246 °C/min and 0.254 °C/min, respectively, so the capsule arrangement served as a suitable heat exchanger. The capsules installed at the top had an average heating rate increase of 111.4% compared to those at the bottom. Therefore, mounting the capsule at the top of the tank was more effective than placing it at the bottom.

Keywords:
Capsule;
Charging;
Paraffin Wax;
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INTRODUCTION

Solar energy is a source of energy for other types of renewable energy [1]. The potential of solar energy in Indonesia is large because it is located on the equator. However, solar energy in the form of thermal energy using SWH can only be used during the day. On the other hand, SWH is mainly used at night when there is no solar energy supply. Under these conditions, the role of thermal energy storage (TES) is essential because it provides energy when it is needed.

The tank is the TES for the SWH system. Water as sensible heat storage (SHS) material is used in conventional SWH. Water has good thermal conductivity but low energy density [2]. The consequence of low energy density is that it requires a large volume of energy storage [3] so that the construction of the SWH system becomes heavy.

The concept of designing the TES system is that the maximum amount of thermal energy can be provided [4]. Based on this concept, to increase the storage capacity of conventional SWH, it is necessary to integrate it with other heat storage materials. For example, paraffin wax is a phase change material (PCM) with a high energy density [2, 5, 6, 7]. Latent heat storage (LHS) using PCM has some advantages: (i) the release of thermal energy occurs in isothermal conditions [8], so it becomes possible to smooth temperature variations [9]; (ii) the storage size is smaller [10] because PCM has a high storage density; (iii) it is very efficient in storing thermal energy [11].

Previous researchers have studied the use of PCM in the active type SWH system. Active type SWH is an SWH system in which the working fluid is circulated using a pump. Combining SHS and LHS in the SWH tank results in more excellent thermal energy storage [12]. The use of water and PCM as thermal energy storage material has better thermal performance than conventional systems [13][14]. PCM placed in the collector causes the exit water temperature to be more stable against fluctuations in the intensity of solar radiation [15] and increases the collector's performance [16]. The use of PCM in the SWH system can reduce thermal losses [17], prevent overheating in the collector [18], and increase the thermal efficiency of the collector [19].

Latent heat thermal energy storage (LHTES) is advantageous for utilizing intermittent heat sources such as solar energy [20]. However, the application of LHTES has a weakness; namely, the speed of charging and releasing heat is slow due to the low thermal conductivity of the PCM [21]. Therefore, it is necessary to improve the thermal performance of LHTES to overcome these shortcomings. One method that can be used to enhance the performance of LHTES is PCM encapsulation [22][23]. Encapsulation is a technique to cover PCM with a specific material [24]. PCM encapsulation can increase the heat transfer rate because the heat transfer surface area increases. Thus, the thermal conductivity also increases [25]. Macro encapsulation is one way to encapsulate PCM in TES applications. The container shape may be spherical, tubular, cylindrical, or rectangular [24].

The use of PCM capsules in SWH tanks has also been investigated experimentally. PCM is contained in vials [26], spherical capsules [12], vertical tube capsules [15], and horizontal cylindrical capsules [27]. For horizontally placed TES tanks, the capsules were arranged along the cross-section of the tank. Previous studies have not revealed the thermal performance of capsules related to their positioning in the TES tank, especially for cylindrical capsules. This paper investigates the thermal energy storage capability of the capsule concerning its mounting position in the tank. The results of this paper can fill the research gap on encapsulation in the SWH TES tank. The experiment used 24 cylindrical capsules arranged symmetrically in a TES tank with a horizontal position.

METHOD

Material

This experiment integrates water and PCM as heat storage materials in the tank. A paraffin wax type of Rubitherm RT52 is used as PCM with a melting temperature of 43 – 52 °C [27]. The function of water is as a heat transfer fluid (HTF). During the charging process, the temperature of HTF increases due to the supply of thermal energy from hot water coming out of the collector. The temperature difference between HTF and PCM causes heat transfer so that the PCM temperature increases.

The schematic diagram of the experiment and its components are shown in Figure 1.

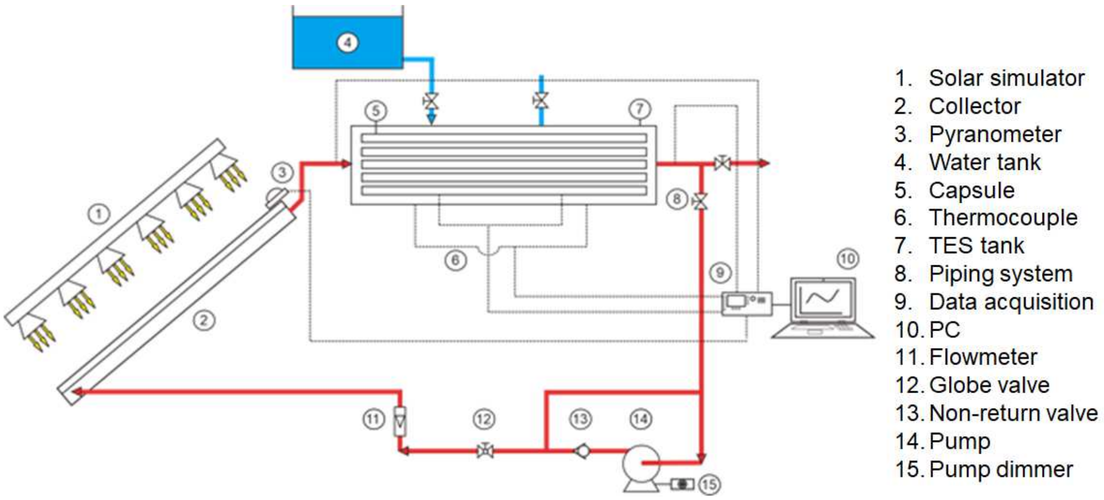

Figure 1. Schematic Diagram of Experiment

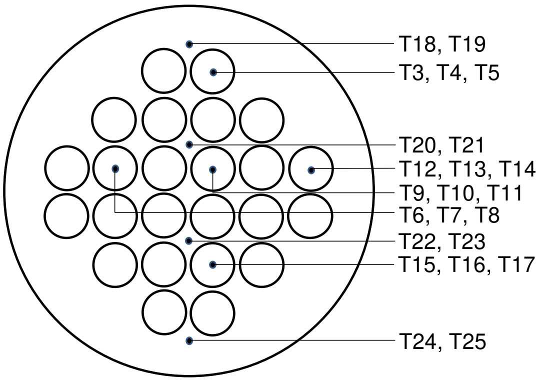

Figure 2. Capsule Arrangement

The main components of this equipment consist of the solar simulator (1), collector (2), TES tank (7), and piping system (8). The TES tank volume is 60 liters. A copper pipe with a length of 100 cm and an outer diameter of 1 inch is used as a capsule (5). Figure 2 shows the 24 cylindrical capsules installed in the tank, and each capsule was filled with paraffin wax.

A piping system connected a flat-plate collector with a surface area of 1.9 m^2 to the TES tank. The solar simulator uses 24 pieces of halogen lamps. The total electrical power of the solar simulator is 7.2 kW. The K-type thermocouples (6) were used to record heat transfer fluid (HTF) and PCM temperatures by an AT4532 multi-channel temperature meter data acquisition (9) and PC (10). A pump of Sharp SPS-109SN (15) was installed in the piping system after the TES tank. Figure 2 shows the arrangement of the capsules in the TES tank. The capsules are installed symmetrically where the axis of the capsule is parallel to the axis of the tank. The number of capsules that are given a thermocouple is five pieces. Each capsule is installed with three pieces of a thermocouple. The capsule numbering is C2 for thermocouple T3-T4-T5, C6 for thermocouple T6-T7-T8, C7 for thermocouple T9-T10-T11, C8 for thermocouple T12-T13-T14, and C12 for thermocouple T15-T16-T17. Figure 2 also shows the mounting positions of eight thermocouples used to record the HTF temperature, namely T18-T19, T20-T21, T22-T23, and T24-T25.

Methods

The first step is to test the heat flux generated by the solar simulator. The pyranometer Hobo Weather Station (3) is placed under the solar simulator at a certain distance. Electrical energy supply is obtained from the voltage regulator by selecting 210 V. The resulting heat flux is recorded for 15 minutes. Then the pyranometer is shifted to another position under the solar simulator. Furthermore, the heat flux results are averaged based on the difference in the position of the pyranometer placement. The same steps are carried out again with a different distance between the solar simulator and pyranometer. The test is completed when it has obtained a heat flux of 1000 W/m^2. This heat flux is a source of energy for the collector. The experiment was carried out during the heating process. The collector, piping system, and TES tank are filled with water from the water tank (4) to the brim. After that, the pump is activated. The pump was adjusted with a pump dimmer (15) until the Omega flowmeter (11) HTF flow rate steadily reached 2 liters/minute. The next step was activating the temperature sensor using a PC. The temperature of HTF and PCM were recorded every minute. HTF and PCM temperatures were recorded for 98 minutes. HTF and PCM temperatures are graphed against time. The temperature evolution of HTF and PCM is used to analyze the heating process in HTF and PCM during charging.

RESULTS AND DISCUSSION

Average Temperature Evolution of HTF and PCM

Figure 3 shows the average temperature evolution of HTF and PCM in the TES tank during the charging process. The average temperature of HTF and PCM is obtained from the average of each temperature reading of all HTF and PCM thermocouples.

Figure 3 describes the HTF temperature at the beginning, and the end of the charging process is 27.20 °C and 51.11 °C, respectively. The increase in HTF temperature constantly occurs with an average heating rate of 0.246 °C/min. The average heating rate is obtained by looking for the temperature difference in each data and then being averaged according to the number of data collections.

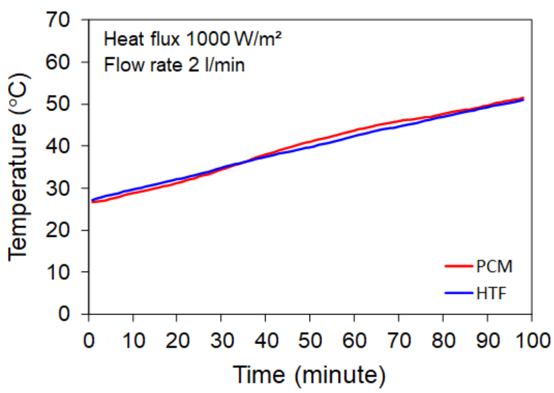

Figure 3. Average Temperature Evolution of HTF and PCM

The increase in HTF temperature is constant due to the constant heat flux from the solar simulator.

Figure 3 also shows that the initial temperature of the PCM is 26.82 °C. After the charging process is complete, the final temperature of the PCM is 51.45 °C. The average heating rate of PCM is 0.254 °C/min. The values of the average heating rate of HTF and PCM are not much different. This condition indicates that the heat transfer in the TES tank has been going well.

Evolution of HTF Temperature

The evolution of HTF temperature in each thermocouple showed in Figure 4(a), and Figure 4(b) shows the evolution of the HTF temperature of each layer. The heat energy generated by the collector is transferred to the TEST tank through the flow of water. This hot water mixes with the HTF in the tank. Figure 4(a) shows that the higher the water layer from the bottom of the tank, the higher temperature tends to be. Thermocouples T18 and T19 are above the inlet line, and thermocouple T19 is located nearby. These two thermocouples have almost the same temperature distribution. Thermocouples T18 and T19 get accumulated thermal energy where the hot water is on the top side of the tank. The highest temperature was obtained by thermocouple T21. The location of the T21 thermocouple placement is close to the inlet line and is at the top of its axis. The temperature of the T21 thermocouple is greater than that of the T19 thermocouple. This occurrence is natural because the input HTF channel is in the middle of the tank.

Figure 4(b) shows the average temperature distribution of each thermocouple pair for each height from the bottom of the TES tank. Each layer of water in the tank is installed with two pieces of thermocouples. The distance between the placement of the thermocouple and the bottom of the tank for each layer is 25 cm (T18 & T19), 17 (T20 & T21) cm, and 9 cm (T22 & T23), and 1 cm (T24 & T25), respectively. The average heating rate for layer 25 cm, layer 17 cm, layer 9 cm, and layer 1 cm are 0.3193 °C/min, 0.3188 °C/min, 0.2298 °C/min, and 0.1176 °C/min, respectively. Figure 4(b) also shows that the temperature distribution of layer 25 cm and layer 17 cm almost coincides. This condition assumes that HTF flows upward from the inlet channel.

Figure 4(b) also informs that thermal stratification has been formed visually in the TES tank. The higher the HTF position, the higher the temperature. Thermal stratification occurs because cold water has a greater density than hot water, so cold water is on the lower side.

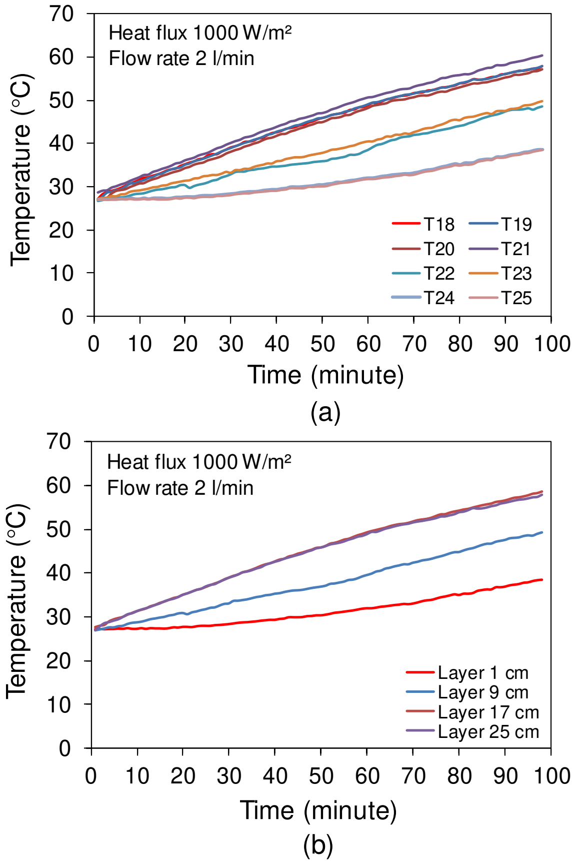

Figure 4. Temperature Evolution of HTF: (a) Each Thermocouple, (b) Each Layer

This phenomenon can increase energy collection efficiency, especially for solar water heating applications. Therefore, stratification technology is widely applied to make household water storage more economical and practical [28]. Based on Figure 4, installing PCM capsules in the TES tank did not prevent the formation of thermal stratification of HTF during the charging process. The SWH system involving PCM in the tank is safe to implement in thermal stratification. Previous research also stated the same thing where PCM installation in the tank positively contributed to the formation of thermal stratification [29].

Evolution of PCM Temperature

The average temperature distribution of PCM capsules during the charging process is shown in Figure 5. The C2 capsule represents the upper capsule in the tank. The capsules in the center of the tank are C6, C7, and C8, while the capsule at the bottom is C12. Figure 5 shows the order of temperature gain from the highest in the upper, middle, and lower capsules.

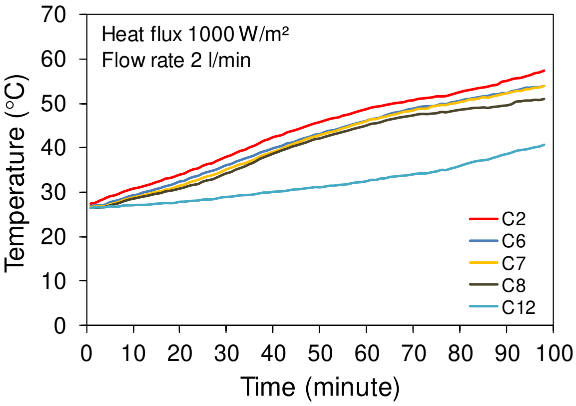

Figure 5. Temperature Evolution of PCM Capsules

The average temperature obtained for paraffin wax capsules of C2, C7, and C12 were 57.50 °C, 54.12 °C, and 40.75 °C, respectively. This phenomenon indicates that the higher the capsule position in the tank, the higher the PCM temperature obtained. Figure 5 shows that the heating rate's average value for capsules C2, C7, and C12 was 0.31 °C/min, 0.282 °C/min, and 0.147 °C/min. The higher the capsule's position, the higher the PCM's average heating rate obtained. The high average heating rate value indicates the large heat transfer received by the capsule.

The impact of differences in thermal energy gain for the height of the capsule position from the bottom of the tank is the formation of HTF thermal stratification. This thermal stratification can improve the storage tank's performance during the charging and discharging process [30][31]. The SWH hot water outlet pipe is generally located at the top of the TES tank. If the HTF temperature in the upper of the tank is high, it guarantees more hot water when being used. However, if hot water and cold water are mixed, the quality of the energy supplied from the TES tank will decrease.

Figure 5 also shows that capsule C6 has a higher temperature than capsules C7 and C8, even though these three are in the center of the TES tank. This condition can be assumed because the HTF flow from the inlet channel does not hit the center of the tank. Further research can be done by installing a flow rectifier so that the hot water spray is evenly distributed along the cross-section of the TES tank.

Based on the technical specifications of paraffin wax RT52, the melting area is 49 – 53 °C. According to Figure 5, PCM has melted except for the C12 capsule. The highest temperature reached by the C12 capsule was 40.75 °C which is still far from the melting temperature. The evolution of the C12 capsule temperature is far below that of other capsules. The tight arrangement of the capsules can cause the low temperature of the C12 capsules because the hot HTF flow does not directly hit them.

Figure 6 shows the temperature distribution of each thermocouple mounted on the capsule. The accumulation of hot water is at the top of the tank so that the HTF temperature is high. The temperature difference between HTF and PCM is also high, so the heat transfer to PCM is also high. Therefore, the temperature of the C2 capsule is the highest. The temperature difference between each thermocouple is visible (Figure 6(a)). Considering the inlet position is in the middle, the hot water spray is not enough to hit the C2 capsule, so there is a temperature difference at T3, T4, and T5. The C6, C7, and C8 capsules are in the center of the tank. The difference in the temperature distribution of each thermocouple is not too significant (Figure 6(b), Figure 6(c), and Figure 6(d)). The location of the C12 capsule is at the bottom of the tank. The thermal energy around the C12 capsule is relatively uniform. As a result, the thermocouple temperature distribution is nearly identical (Figure 6(e)).

From Figure 6, we can see that the lower the capsule's position, the thermocouple temperature difference in each capsule is not much different. The lower the HTF layer, the lower the thermal energy content. The temperature difference between HTF and PCM is also low, so not much heat is transferred to PCM. Therefore, installing the capsule at the bottom of the tank does not provide a significant advantage in terms of thermal energy storage.

Previous research on the use of PCM capsules in SWH tanks generally agrees with the results of this paper, although the placement of the tanks is different (in vertical position). Mounting the PCM capsule at the top of the vertical tank allows hot water for a more extended period, even without an external energy supply [12]. A copper cylindrical capsule containing paraffin wax was introduced into the SWH tank and concluded that the water temperature increased more rapidly at higher tank positions [32]. The addition of capsules containing PCM in the upper vertical tank can increase the thermal performance of the tank, where the decrease in water temperature is 8.5% longer than the tank without PCM [33][34]. All of these studies confirmed that installing the capsule at the top of the tank could improve the thermal performance of water.

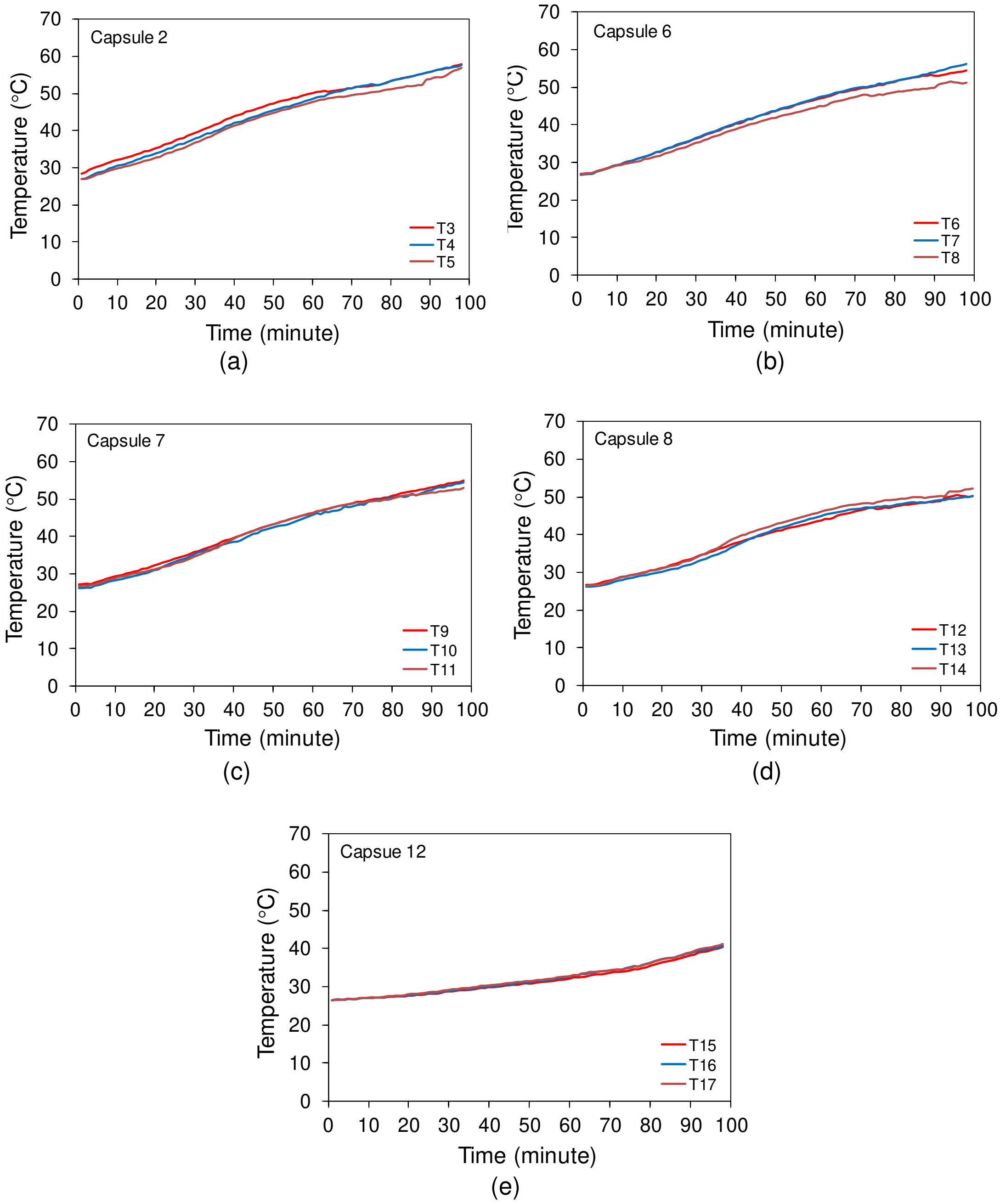

Figure 6. Temperature Evolution of PCM Capsules; (a) C2, (b) C6, (c) C7, (d) C8, (e) C12

CONCLUSION

Experimental investigations on the HTF and PCM temperature evolution in an active-type of SWH containing PCM have been carried out. The solar simulator that produces constant heat flux can show the evolution of HTF and PCM temperatures well. The average heating rate of HTF and PCM is 0.246 °C/min and 0.254 °C/min, respectively. The value of the average heating rate is not much different. Therefore, the composition of the PCM capsules inside the tank has functioned as a heat exchanger well. The SWH system, which contains PCM, contributes to thermal performance due to thermal stratification formation. The location of the capsule in the tank affects the thermal energy gain for the PCM. The average temperature of paraffin wax obtained during the charging time of 98 minutes for capsules C2, C7, and C12 was 57.50 °C, 54.12 °C, and 40.75 °C, respectively. The average heating rate of capsules C7 and C12 to C2 increased by 92.23% and 111.4%, respectively. The capsule placement at the top of the TES tank is most effective because it obtains the most significant thermal energy. Otherwise, capsules placed at the bottom are less capable of storing thermal energy. Future research is advised not to install PCM capsules at the bottom of the tank.

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