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Latent Heat Storage in a Two-Phase Thermosyphon Solar Water Heater

This article experimentally studies the thermal performance of latent heat storage in a two-phase thermosyphon solar water heater, which utilizes the superior heat transfer characteristics of boiling and condensation, and eliminates drawbacks found in the conventional solar water heater. Experimental investigations are first conducted to study the thermal behavior of tricosane (paraffin wax 116), water, and sodium acetate (NaCH₃COO·3H₂O) used as energy storage materials. The results indicate that tricosane provides many advantages to be the energy storage material in the latent heat storage system. This study also examines the functions of charge and discharge thermal behaviors in a two-phase thermosyphon solar water heater. The results show that the system gives optimum charge and discharge performance under 40% alcohol fill ratio and with tricosane used as the energy storage material, and displays an optimum charge efficiency of 73% and optimum discharge efficiency of 81%. [DOI: 10.1115/1.2147588]

Keywords: energy storage material, two-phase thermosyphon, solar water heater

1 Introduction

A number of solar water heaters [1] have been considered and developed in recent years. Most solar water heaters utilize an active control method to store or release thermal energy. That is, in designing heat storage, a pump is included to transfer thermal energy from the collector to the thermal storage tank via flowing working fluid. To utilize the stored thermal energy, an electromagnetic valve is used under control to change the flow path of the working fluid, so that energy stored in the storage tank is released to the domestic water. There are two drawbacks found in such solar energy systems. First, the thermal storage shall be unusable in case of pump or electromagnetic valve failure. Second, the charge and discharge ability of the conventional storage systems basically relies on the system piping design, and therefore, only two functions, energy storage and energy release, are available in its operating modes.

The objective of the present article is to provide a two-phase thermosyphon solar water heater [2] in which a passive type of control is adopted to eliminate the above drawbacks found in the conventional solar heating systems. Moreover, apart from storing and releasing energy, the proposed solar water heater also allows for operation of the energy supply side and energy use side at the same time [2]. The two-phase thermosyphon solar water heater, as shown in Fig. 1, mainly includes an energy storage tank and twophase thermosyphon loops. The energy storage tank is filled with energy storage material (ESM). The thermosyphon loops include three parts, namely, a group of parallel fin tubes vertically disposed inside the storage tank, the vertical collector tubes located outside of the tank and a horizontal double pipe heat exchanger situated at the upper region inside of the storage tank. An adequate amount of working fluid is filled in the thermosyphon loops. The parallel fin tubes combine the collector tubes to form a two-phase closed loop thermosyphon for thermal storage. The thermal release process is achieved by connecting the parallel fin tubes and the double pipe heat exchanger to form a two-phase closed thermosyphon.

Figure 1(a) shows the function in which the system operates to store thermal energy. The working fluid, ethyl alcohol, inside the collector tubes, having absorbed solar radiation, becomes boiled and produces gaseous working fluid which flows upward due to its buoyancy into the double pipe heat exchanger and then downward into the parallel fin tubes. The alcohol vapor condenses and releases heat to the ESM outside of the parallel fin tubes. The condensed working fluid flows downward along inner surfaces of the parallel fin tubes under gravity and into the lower header, and finally into the collector tubes to complete charge cycle.

Figure 1(b) shows the manner in which a system operates to release thermal energy. When the cold water enters the internal tube of the double pipe heat exchanger, ESM will release heat. The liquid working fluid in the parallel fin tubes absorbs heat stored in the ESM and becomes boiled to produce vapor working fluid which flows upward due to its buoyancy. As heat is transferred to cold water, the vapor working fluid undergoes condensation on the outside of the internal tube of double pipe heat exchanger. Then the condensate flows along the wall of parallel fin tubes, absorbs heat from ESM and becomes boiled to complete discharge cycle.

The distinguishing feature of the proposed integral collectorstorage system can make the thickness of the solar water heater thinner and the weight of storage tank lighter, as compared with the conventional heating system. Thus the cubic configuration of the present design could be utilized in many applications where the conventional solar collectors cannot be applied. For instance, it can be readily installed as the wall or roof of a building, which better utilize the space of the building and reduce the solar heating load to the building. It is very suitable in Taiwan, where the cooling load for an air conditioner comes mostly from solar heating. It is also suitable for regions where the water quality is very poor; for example, at the south part of Taiwan people use solar energy to heat underground water. Scaling would take place inside of the storage tank in the conventional solar collectors, which results in bad heat transfer and corrosion problems. In the proposed energy storage system, the double pipe heat exchanger is used to release the stored heat from the storage tank to the cold water. It can prevent the corrosion inside of the storage tank.

Many factors affect the thermal performance of a two-phase thermosyphon solar water heater [2]. In view of the application, we focus on the choice of ESMs. In this paper, two experimental

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Fig. 1 Thermal storage in two-phase thermosyphon solar water heater (a) charge mode, (b) discharge mode

systems are developed. In the first experiment, the thermal behaviors of three ESMs, including tricosane (paraffin wax 116), sodium acetate (NaCH₃COO·3H₂O), and water are investigated. Applying the results from the first experiments, the thermal performance of a two-phase thermosyphon solar water heater is experimentally described. This study also examines the effect of the alcohol fill levels on the charge and discharge characteristics in the proposed solar water heater.

2 Experiments in Energy Storage Materials

Energy storage material plays a significant role in the energy storage system. To find a better ESM for a heating application, numerous research works have been carried out and reported. Most of the investigations were focused on paraffins, nonparaffin organics, fatty acids, salt hydrates, and eutectics of organic and inorganic compounds [3–6]. In this paper, three materials, tricosane (paraffin wax 116), sodium acetate (NaCH₃COO·3H₂O), and water were used to study the characteristics of the ESM. Although water is not a latent heat medium for the operating temperature range, it is easy to acquire and in common use for solar heat storage application. For this reason, we use water as the baseline and compare the results with other phase change materials.

Figure 2 shows the schematic of measuring apparatuses used for obtaining the thermal characteristics of ESM during charge and discharge experiments. The volume of each specimen of ESM in the test tube is 20 cc. The test tube is covered by 1.9 cm thick insulation. Heat input is achieved by connecting the ac power supply to heating wire (resistance heater) and is calculated form the product of voltage and current, within approximately 5% error. Each ESM stored energy from the initial temperature of 30°C to the end temperature of 70°C. During heat discharge, the test tube was settle in the glass cup and released heat by natural convection to the surroundings. The initial temperature of each ESM was 70°C for the discharge process, with a final temperature of 30°C.

Salt-hydrates, characterized by M.*n*H₂O, where M is an inorganic compound, form an important class of heat storage substances due to their high volumetric latent heat storage density. The major problem in using salt hydrates as ESM is that most of them melt incongruently, i.e., they melt to a saturated aqueous phase and solid phase which is generally a lower hydrate of the same salt. Due to density differences, the solid phase settles out and collects at the bottom of the container. During solidifying, the solid phase does not combine with the saturated solution to form the original salt-hydrate. Another important problem is their poor nucleating properties resulting in supercooling of the liquid salthydrate prior to solidification [3]. Therefore, thickening agents or nucleating agents are generally needed.

It is well-known that paraffin waxes qualify as latent heat phase



Fig. 2 Schematic of measuring apparatus used in the ESM experiments

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Fig. 3 Temperature variations of each ESM during the heat storage process

change materials due to their applicability over large temperature ranges and having high heats of fusion. Paraffin waxes are saturated with hydrocarbon mixtures, which normally consist of a mixture of mostly straight chain alkanes, characterized by C_nH_{2n+2} . The *n*-alkane content in paraffin waxes usually exceeds 75% and may reach 100%. The crystallization of the $(CH_2)_n$ chain releases a large amount of the latent heat. Various paraffin waxes with a range of melting temperatures are available. For the solar water heater, the ESM should have a phase change temperature of approximately 40–60°C. Therefore, tricosane (paraffin wax 116) was chosen as the ESM. These substances are nontoxic, noncorrosive and chemically inert. Furthermore, paraffin waxes present little fire hazard, and they have been used as ESM for thermal energy storage in greenhouses [6].

The ESM utilizes sensible heat in the solid and liquid phases and latent heat during phase change. Therefore, the stored heat of the ESM, Q_{ch} , may be computed based on sensible heat and latent heat as shown in the following equation:

$$Q_{\rm ch} = \sum_{j=0}^{t_b} Mc_s (T_{j+\Delta t} - T_j) + Mh_{sl} + \sum_{t_e}^{\rm time} Mc_l (T_{j+\Delta t} - T_j)$$
(1)

During solidifying of the ESM, the released heat of the system, Q_{disch} , may be computed based on the following equation:

$$Q_{\text{disch}} = \sum_{j=0}^{t_b} Mc_l(T_j - T_{j+\Delta t}) + Mh_{sl} + \sum_{j=t_e}^{\text{time}} Mc_s(T_j - T_{j+\Delta t}) \quad (2)$$

Figure 3 illustrates temperature variation of three ESMs during the heat storage process. Due to the different thermo-physical properties of each ESM, the ending time of each ESM in the charge experiment is different. The ending time of sodium acetate is the longest (about 4200 s) and the ending time is 3000 s for tricosane and 2500 s for water. It reveals that utilizing sodium acetate as the ESM could store more thermal energy during the same temperature difference. Initially during the charge process, the temperature slope of water is less than others. It is because the specific heat of water is larger and it shows the best performance in the range of sensible heat storage. In the process of latent heat storage, tricosane and sodium acetate show nearly constant temperatures during phase change.

Table 1 Thermo-physical properties of energy storage materials

Material		Tricosane	Sodium acetate	Water
Molecular formula		C23H48	NaCH ₃ COO · 3H ₂ O	H ₂ O
Melting point (°C)		45-47	57–58	Ő
Heat of fusion (kJ/kg) ^a		210	226	333
	solid	817	1450	917
Density (kg/m ³) ²	liquid	786	1280	998
	solid	2.89	1.7	2.09
Specific neat (KJ/Kg-K)	liquid	2.89	2.79	4.18

^aData from [3].

^bData from [3,8].

Figure 4 indicates temperature variations of the three ESMs during the heat release process. The temperature curves of sodium acetate with and without nucleating agent are also shown. During the heat release process, the initial temperature of each ESM at 70°C produces a liquid state. The temperature of tricosane drops to its solidification temperature, 47°C and solidification occurs at this temperature. However, solidification for sodium acetate does not occur at its phase change temperature, 58°C. It still maintains as a supercooled liquid state. Supercooled liquid refers to a metastable state, which will be ended by producing a vibration disturbance on the tube wall when the temperature is cooled to about 50°C. After applying the slight vibration, nucleation occurs and the thin platelike crystal grows into the supercooled region. During the crystal growth process, latent heat released from the crystal is consumed by supercooled liquid. At the end of the growth process, the temperature of liquid is returned to its solidification temperature (58°C) and the stored energy is released. Without vibrator disturbance, the meta-stable state exists and remains during the heat storage process, as shown in the temperature history of sodium acetate without nucleating agent, and the thermal energy can only be released in the form of sensible energy. This phenomenon is called supercooling and is a serious problem in applying salt-hydrates as the ESM in the heat storage system. In the contrast, the temperature of tricosane drops to its solidification temperature (47°C) and solidified without supercooling. It should be noted that the operating temperatures for the discharge experi-



Fig. 4 Temperature variations of each ESM during the heat release process

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Table 2 Experimental results of stored heat for each ESM from 30°C to70°C

Material	Stored heat per unit volume (kJ/L)	Relative index	Stored heat per unit mass (kJ/kg)	Relative index
Tricosane	269 ± 14.5	1.57	345 ± 18.5	2.01
Sodium acetate	385 ± 20.5	2.25	301 ± 15.9	1.75
Water	171 ± 9.5	1	172 ± 9.5	1

ment are fixed (discharge temperature of each ESM is 70° C to 30° C); therefore, the ending time is different. Energy storage material with longer ending time indicates more heat discharge. The operating time for tricosane and sodium acetate with nucleating agent is about 3800 s and that of water is about 3100 s, while that for sodium acetate without nucleating agent is 2260 s.

Table 2 shows the experimental results of stored heat for tricoscane, sodium acetate, and water from 30° C to 70° C. In the table, relative index is the ratio of stored heat in ESM to the stored heat in water. The heat capacities of tricosane and sodium acetate are higher than water, which demonstrates that latent heat storage provide better performance than sensible heat storage. Under the conditions of the same storage volume, tricosane and sodium acetate can store 57% and 125% more heat than water, respectively. For the case of the same mass, tricosane and sodium acetate have 101% and 75% higher thermal capacities than water, respectively. It is obvious that sodium acetate has the best storage performance among three ESMs. However, supercooling occurs during the solidification of sodium acetate, and nucleating agents are needed in order to overcome the problem.

3 Experimental Investigations in the Two-Phase Thermosyphon Solar Water Heater

As shown in Fig. 5, the two-phase thermosyphon solar water heater comprises a solar collector, double pipe heat exchanger, fin tubes inside the storage tank, and lower headers. The solar collector consists of ten vertical copper tubes and a heating plate covered by thin foil heaters is used. The storage tank is made of 3 mm thick stainless steel plates. In the storage tank, two rows of fin tubes with 18 fins per inch are mounted. Two headers each are connected at the top and bottom of the storage tank, the two upper headers are copper tubes sealed with copper stoppers on both ends



Fig. 5 Diagram of the two-phase thermosyphon solar water heater, (1) collector, (2) double pipe heat exchanger, (3) fin tubes, (4) lower headers, (5) energy storage tank

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Table 3 Dimensions of the solar water heater

Component	Dimension	Unit
Collector		
area	0.9	m ²
width	1000	mm
Energy storage tank		
length	200	mm
height	690	mm
width	960	mm
length of fin tubes	850	mm
diameter of lower header	19	mm
Double pipe heat exchanger		
diameter	19	mm
length	970	mm
-		

and contain an internal stainless steel fin tube working as a double pipe heat exchanger during heat discharge. Insulation material at the outside of storage tank prevents heat losses during the experiment. The dimensions of the solar water heater are shown in Table 3.

Figure 6 is a schematic of the measuring apparatus used in the experiment for obtaining primarily temperatures and water flow rates. Temperature measurement utilizes T-type thermocouples with 0.3 mm probes and a data recorder. Five points (T1–T5) measure the ESM temperatures; two points (T6 and T7) are set at the inlet and outlet of the double pipe heat exchanger to measure the water temperatures. Tricosane, sodium acetate and water are used as the ESM and alcohol is used as the working fluid inside the two-phase thermosyphon, the heat input is 1300 W in the charge process. For heat discharge, the water flow rate is 3 lpm. Both charge and discharge periods are eight hours.

The fill ratio, V_f , expressed by volume percentage, may be defined as follows:

$$V_f = V_t / V_t \times 100\% \tag{3}$$

where V_r means the actual volume of working fluid, V_t means the total volume of the thermosyphon loop, which was 14,468 ml by measurement. The operating conditions cover fill ratios from 30% to 60%. The liquid level of the working fluids and the corresponding temperature measurement points for ESM in storage tank are also shown in Fig. 6.

The charged heat of the system, Q_{ch} , may be computed based on the temperature rise of the ESM, $\Delta T_{i,j}$, as shown in the following equation:

$$Q_{\rm ch} = \sum_{j=0}^{t_b} \sum_{i=1}^5 M_i c_s \Delta T_{i,j} + \sum_{i=1}^5 M_i h_{sl} + \sum_{t_e}^{8 \, \rm hr} \sum_{i=1}^5 M_i c_l \Delta T_{i,j} \qquad (4)$$

where $\Delta T_{i,j} = (T_{i,j+\Delta t} - T_{i,j})$. Heat input, Q_{in} , is obtained from the product of electric input power *P*, and operating time t_{op} , which is eight hours.

$$Q_{\rm in} = P \cdot t_{\rm op} \tag{5}$$

The energy calculations for heat discharge include discharged heat, Q_{dis} , and effective heat output, Q_{eff} . The discharged heat may be obtained from the temperature drop of the ESM ($\Delta T_{i,j}$) as shown in the following equation:

$$Q_{\rm dis} = \sum_{j=0}^{t_b} \sum_{i=1}^5 M_i c_l \Delta T_{i,j} + \sum_{i=1}^5 M_i h_{sl} + \sum_{j=t_e}^{8 \text{ hr} 5} \sum_{i=1}^5 M_i c_s \Delta T_{i,j}$$
(6)

where $\Delta T_{i,j} = (T_{i,j} - T_{i,j+\Delta t}).$

The effective heat output, Q_{eff} , indicates the thermal energy actually obtained from the energy discharged, which may be obtained from the temperature difference between inlet and outlet of cold water in the double pipe heat exchanger.

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Fig. 6 Schematic of measuring apparatus used in the experiment

$$Q_{\rm eff} = \sum_{j=0}^{8} \dot{m} c \Delta T_j \tag{7}$$

where $\Delta T_j = (T_{\text{out},j} - T_{\text{in},j})$.

The charge efficiency is the ratio of heat stored in the ESM to heat input from power supply. The discharge efficiency is the ratio of effective absorbed heat from double pipe heat exchanger to heat released from energy storage material.

$$\eta_{\rm ch} = \frac{Q_{\rm ch}}{Q_{\rm in}} \tag{8}$$

$$\eta_{\rm dis} = \frac{Q_{\rm eff}}{Q_{\rm dis}} \tag{9}$$

According to the uncertainty analysis proposed by ISO standard [7], the uncertainties of charge and discharge efficiency with 40% fill ratio are obtained. The results for charge efficiency are $\pm 4.49\%$, $\pm 3.98\%$, and $\pm 4.68\%$ for tricosane, water, and sodium acetate, respectively. The corresponding results for discharge efficiency are $\pm 4.86\%$, $\pm 3.24\%$, and $\pm 3.02\%$

The energy balance equation for the charge process can be expressed as

$$Q_{\rm in} = \sum Q_{\rm ch} + \sum Q_l \tag{10}$$

The power input, Q_{in} is equal to the total stored heat, ΣQ_{ch} , and the total heat loss, ΣQ_l . The total stored heat includes the stored heat in ESM, Q_{ch} , the stored heat in system body, Q_{Csb} , and the stored heat in working fluid, Q_{Cwf} . The total heat loss includes the heat loss from energy storage tank to surroundings, $Q_{loss,l}$, and the heat loss from heating plate to surroundings, $Q_{loss,p}$. The heat loss from the energy storage tank to the surroundings is calculated from the heat loss coefficient of energy storage tank, the area of the system and the temperature difference between the tank and surrounding. The stored heat in system body and the stored heat in working fluid are calculated from the temperature, the mass, and the specific heat of the system components and working fluid. Then $Q_{\text{loss},p}$ can be obtained from Q_{in} minus Q_{ch} , Q_{Csb} , and Q_{Cwf} .

Table 4 shows the experimental results of charge efficiency and heat losses for three different ESMs. As can be seen, the stored heat in the working fluid and in the system body are very small compared with the heat stored in PCM, no matter what kind of ESM is used. The heat losses from heating plate to surroundings are 17.9%, 41.8%, and 15.3% for tricosane, water, and sodium acetate, respectively, which is the dominant component in total heat loss. Note that the charge efficiency with PCM as ESM is higher than water because of their high heat capacities.

Many factors affect the charge or discharge efficiency, such as working fluids; fill ratios, and energy storage materials. These factors make the system operate at different temperatures and thus affect the thermal performance.

Figures 7(a)-7(c) show temperature variations (T1–T5) of tricosane, water and sodium acetate, respectively, during heat

Table 4 Charge efficiencies and heat loss percentages

ESM	$Q_{\mathrm{loss},t}/Q_{\mathrm{in}}$	$Q_{\mathrm{loss},p}/Q_{\mathrm{in}}$	$Q_{Cwf}/Q_{\rm in}$	Q_{Csb}/Q_{in}	$\eta_{ m ch}$
Tricosane	3.2%	19.6%	1.5%	1.7%	74%
Water	2.8%	47.4%	1.7%	1.1%	47%
Sodium acetate	2.7%	17.0%	1.1%	1.2%	78%

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Fig. 8 Temperature distributions of (a) tricosane, (b) water, and (c) sodium acetate, during the heat discharge process

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Fig. 9 Comparison of charge efficiencies under different fill ratios

charge, for a fill ratio of 40% and heat input of 1300 W. Tricosane and sodium acetate undergo three periods, i.e., solid state, phase change and liquid state, while water remains liquid. Since the fill ratio is 40%, as shown in Fig. 6, the temperature measurement points T1-T3 are above the alcohol level, where is the effective condensation region in the thermosyphon. In this region the ESM has the same temperature profiles and the thermal stratification of ESM does not appear. This is due to the fact that film condensation occurs inside the thermosyphon and keeps the temperature of the ESM uniform. At the region below the alcohol level, the temperature profiles of T4 and T5 show serious thermal stratification. In order to reduce the effect of thermal stratification, the fill ratio should be as low as possible in the condenser section. However, the smaller fill ratio will also shorten the effective boiling regions, as the working fluid is boiling in the collector. Therefore there exists an optimum fill ratio, which gives the best charge performance.

Figures 8 depict temperature variations of tricosane, water, and sodium acetate used as the ESM during the discharge process for the case of 40% fill ratio. Tricosane in Fig. 8(a) releases heat to the double pipe heat exchanger and undergoes a phase change period, i.e., the temperature curve is approximately flat in the middle period. In Figs. 8(b) and 8(c) water and sodium acetate remain in the liquid state and release the sensible heat. Thermal stratification is not serious inside the storage tank. This is due to the fact that different heat transfer mechanisms occur inside the thermosyphon. As shown in Fig. 1, in the region above the alcohol fill level, film evaporation is the dominant heat transfer mechanism, while pool boiling appears in the region below the fill level. These two high heat transfer mechanisms destroy the thermal stratification, as the discharged process proceeds. It should be noted that in Fig. 8(c) sodium acetate without a nucleating agent is used as the ESM, and the supercooling appears. Supercooled liquid exists inside the storage tank and the energy is released by sensible heat. Since the heat capacity of sodium acetate is smaller than water, the temperature profiles drop quicker than those of water during the initial stage of the discharge process.

Figure 9 shows the charge efficiencies under different fill ratios and different ESMs. The system using tricosane as the ESM has an optimum charge efficiency of 73% at 40% alcohol fill ratio. Sodium acetate has an optimum charge efficiency of 81% at al-



Fig. 10 Comparison of discharge efficiencies under different fill ratios

most the same fill ratio. While using water as the ESM, the optimum charge efficiency is 43%. Figure 10 demonstrates the discharge efficiencies under different fill ratios and different ESM. The optimum discharge efficiency for tricosane is 81% at 40% fill ratio. With water and sodium acetate as the ESM, the optimum discharge efficiency is 64% and 20.5%, respectively. Tricosane shows better thermal performance than water for both charge and discharge.

4 Conclusion

Three different energy storage materials are investigated in the two-phase thermosyphon solar water heater. Based on the experiments and results just discussed, tricosane qualifies as the best ESM for thermal storage since it has a reasonably high latent heat. Furthermore, it is able to solidify and melt repeatedly and congruently. Due to its self-nucleation property, it can be solidified without supercooling. In addition, the heat storage efficiency and the heat discharge efficiency using tricosane as the ESM are 30% and 17% higher than with water, respectively. The results also show that an optimum alcohol fill ratio of approximately 40% exists for the optimum performance of the proposed solar water heater, regardless of whether the energy storage material is tricosane or water. Using tricosane as the ESM, the optimum heat storage efficiency of the energy storage system is 73% and its optimum heat discharge efficiency is 81%.

Nomenclature

- c = specific heat (J/kg-K) $h_{sl} =$ heat of fusion (J/kg) M = mass of ESM (Inc)
- M = mass of ESM (kg)
- \dot{m} = mass flow rate (kg/s)
- P = power(W)
- $Q_{\rm ch}$ = stored (or charged) heat (J)
- $Q_{\rm eff}$ = effective heat (J)
- $Q_{\rm dis}$ = released (or discharged) heat (J)
- $Q_{\rm in} = \text{heat input (J)}$
- $Q_{\text{loss},t}$ = heat loss from energy storage tank to the surrounding (J)
- $Q_{\text{loss},p} = \text{heat loss from heating plate to the surrounding}$ (J)

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 Q_{Csb} = stored heat in system body (J)

 Q_{Cwf} = stored heat in working fluid (J)

 $T_{\rm in}$ = inlet temperature (K)

- $T_{\rm out}$ = outlet temperature (K)
 - t = time (sec)
 - $t_b =$ time at the beginning of solidification or melting (sec)
 - $t_e = \text{time at the end of solidification or melting} (sec)$
- time = ending time of experiment (sec)
 - V_r = volume of working fluid (ml)
 - V_t = total volume in thermosyphon loop (ml)

Greek symbols

 ρ = density (kg/m³)

Subscripts

- i = level no. of ESM inside storage tank
- j = time no. during charge or discharge process
- l = liquid state
- s = solid state

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