Experimental comparative performance testing of solar water heaters

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Abstract

Performance testing of solar heating systems and solar collectors according to International Standard Test procedures require sophisticated and expensive elaborate set-ups. Outdoor collector testing is not feasible in countries with widely fluctuating solar radiation conditions. Indoor testing does not give its true performance when the equipment is situated outdoors. This paper reports on a simple test procedure where the performances of the flat plate, U-tube and heat pipe natural convection solar heaters and the heat pipe force convection solar heater, which were tested on different days, were compared as if they were simultaneously tested side by side. The procedure allowed: (i) the maximum hot water storage temperature that could be achieved by the system over a long period of time without any water draw-off at all, (ii) overnight water temperature drop in the storage tank and (iii) expected end-of-day water temperature and mean system efficiency when water is completely drained down (draw-off) in the evening. Maximum temperatures reached for the natural convection heat pipe, force convection heat pipe, flat plate and U-tube system were 100, 84, 65 and 50°C, respectively. Overnight temperature drops due to standing tank loss and reverse flow were presented and found to be dependent upon initial tank temperature. By pro-rating all the results to reflect on the same area/volume ratio, the expected water temperature rise for the U-tube, forced convection heat pipe, flat plate and natural convection heat pipe systems was 13.6, 17.6, 20.6 and 28.4°C, respectively.

Keywords: solar water heater; flat plate collector; U-tube collector; heat pipe collector; system performance

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1 INTRODUCTION

The natural convection or thermosyphon flow solar water heater (SWH) shown in Figure 1 operates on the principle of thermal buoyancy. The solar collector heats up the water in the tubes of the collector plate which rises up the upriser pipe to the storage tank. Denser cold water in the storage tank flows down the downcomer pipe. This natural recirculating flow of water occurs throughout the day as long as heat is absorbed in the solar collector. As a result, the temperature of the water stored in the insulated storage tank increases. The performance of the system depends mainly on the system design, ratio of the collector plate area to volume of the storage tank, angle of inclination of the collector and environmental factors like solar radiation intensity, ambient temperature and wind conditions. The insulation quality of the tank would contribute to standing heat loss from the tank throughout. To a large extent, the relative height between the tank and collector would determine the overnight water temperature drop due to reverse flow circulation at night. A force circulation system that incorporates a pump to circulate the water between the solar collectors and the storage tank would not suffer from reverse flow heat losses. However, if a heat exchanger is incorporated in the solar collection loop, there would be a loss in performance.

SWHs have been tested since the early 1970s. Classical solar collectors then were of the tube-in-fin flat-plate types. Since then new developments have resulted in more efficient collectors with evacuated tubes and selective surfaces. Experimental investigations on these include the all-glass (Morrison and Budihardjo, 2004), [1–4], U-tube [5, 6] and the heat pipe [7], to name a few. The evacuated tubes minimize convective heat losses from the collectors while selective surface reduces emissive heat losses. ISO Test standard Part 1 [8] establishes a uniform indoor test method for rating domestic solar water heating systems with solar simulators. It is neither practical nor feasible to conduct outdoor tests on solar collectors in a tropical country like Malaysia which is subjected to widely fluctuating and intermittent solar radiation. Indoor tests are

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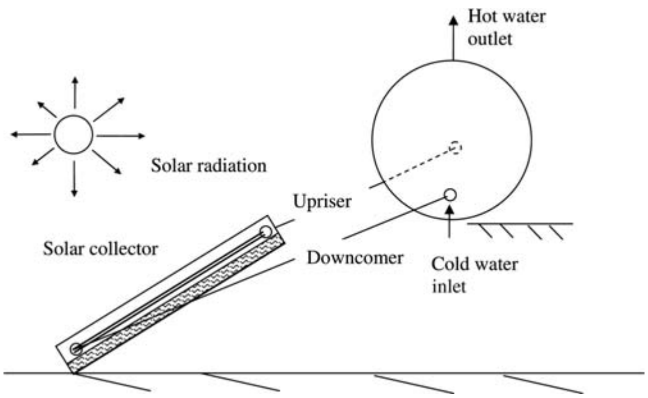

Figure 1. *Schematic of a natural convection solar water heater with a flat-plate collector.*

expensive to conduct and would not provide meaningful information to the domestic or commercial end-user. Outdoor system tests would be more informative to the consumers who need to decide on which system to purchase. Comparative outdoor system performance tests on the available systems would assist them on their choice of product to purchase. There is thus a need for a simple inexpensive procedure to enable outdoor system tests of various SWHs which are conducted at different times of the year to be compared as if they were tested simultaneously, side by side. This method would obviate the need to repeat tests should the need arises for side-by-side simultaneous comparative performance testing. The present method is similar to the ISO Test standard Part 2 [9] which establishes test procedures for characterizing the outdoor performance of solar domestic water heating systems with evening draw-off. However, the procedure does not allow the maximum temperature that could be obtained from the SWH system to be determined. Also, it does determine the overnight temperature drop to be obtained at various hot water storage temperatures.

2 OBJECTIVE

In this paper, the results of tests on four SWH systems conducted at different times of the year are compared using a long-term test series conducted over several days without any water draw-off and a short-term test series conducted over 24 h with complete water drain down (draw-off). This is possible because seasonal variation in Malaysia is minimal.

3 EXPERIMENTAL METHODOLOGY

3.1 Long-term tests without water draw-off

This series is performed without any water draw-off from the system. Performance of a solar system depends upon weather conditions. Long term here means over a period of at least 7 days or more as required. The test should cover a sufficient period of time in order to obtain results over reasonably widespread weather conditions. This series would enable the maximum hot water storage temperature that could be achieved over a period of time to be obtained. Overnight heat losses result from standing storage tank heat loss and reverse flow at night. Standing heat loss depends upon quality of storage tank insulation. Most storage tanks are insulated with 50 mm thick polyurethane foam. Reverse flow occurs in SWH systems at night when the storage tank water temperature is high and the collectors reject heat to the cold ambient night. Reverse flow depends upon the relative heights between the collector and storage tank—the higher the tank is with respect to the collector, the less is the reverse flow. The extent of temperature drop is also dependent upon the mean storage tank water temperature during the night. This long-term test would enable the overnight water temperature from 5 p.m. (say) in the evening to 7 a.m. the next morning to be determined. There are many factors to determine weather conditions at night (e.g. sky temperature, ambient temperature, wind, rain, etc.). In this paper, the ‘starting’ mean tank temperature at 5 p.m. is noted.

3.2 Short-term tests with daily water draw-off

This series is performed by draining off all the water in the storage tank at the end of the day and filling it up with fresh water for the next day’s test. End-of-day could be assumed to occur in the evenings any time from 5 p.m. as the Sun is not able to produce any more heating effect after this time. A test day could also commence from midnight or before the sun rises in the morning. Since performance of a solar system depends upon weather conditions, it is recommended that a sufficient number of days of tests be carried out to obtain results over reasonably widespread weather conditions. This daily test series would enable the average temperature of the hot water in the storage temperature and the mean system efficiency to be obtained. It is important to obtain the mean system efficiency in order to compare equivalent collector area/tank volume ratio for each system.

4 EXPERIMENTAL INVESTIGATION

4.1 Apparatus

The following SWH systems were tested:

System A. Tube-in-fin flat-plate SWH under natural convection (FP).
System B. U-tube SWH under natural convection (UT).
System C. Heat-pipe SWH under natural convection (NC).
System D. Heat-pipe SWH under forced convection (FC).

The collectors are illustrated in Figure 2. Systems B, C and D were tested simultaneously while System A was tested at a different time.

Figure 3 shows a photograph of systems B, C and D installed on the roof of Monash University Sunway Campus. The solar collectors were mounted on steel supporting structures at angles of ~20° to the horizontal. For the natural convection systems A, B and C, the collectors were closely coupled to identical 270 l horizontal insulated hot water storage tanks. For the U-tube system B, the collectors were mounted in a vertical position below the storage tank. The U-tube collectors are meant to be mounted on balconies of high-rise apartments. The heat pipe force convection system D was an indirect system with a heat exchanger inside a vertical 200 l storage tank located one floor below the roof and is not shown in the photograph. A small water pump circulates water between the heat pipe solar collectors and the heat exchanger in the tank. It is controlled by two differential temperature sensors installed at the bottom of the tank and the outlet of the collectors. Circulation started when the temperature differential was at 10°C and stops when it was at 5°C. The U-tube and heat pipe collectors were enclosed in evacuated glass tubes with selective coatings applied on the inner surface of the glass. The flat-plate collector was glazed with a 4 mm thick glass sheet and the absorber surface was painted matt-black. Tank capacities and collector areas are tabulated in Table 1. The horizontal tanks were fabricated from 1.2 mm thick stainless steel inner tank and 50 mm thick polyurethane insulation. The vertical storage tank was fabricated from 1.2 mm thick mild steel and enamel coated to prevent corrosion. Details of the heat exchanger are not available from the manufacturer.

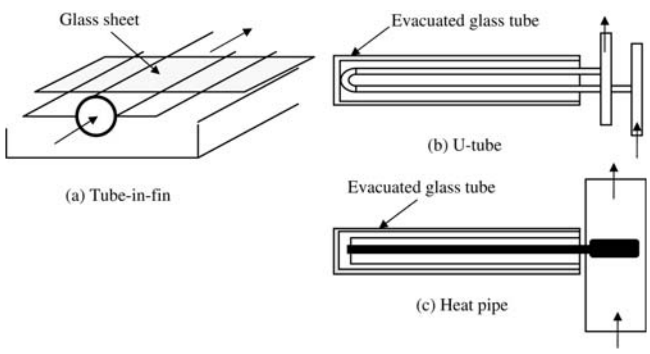

Figure 2. *Types of solar collectors.*

Table 1. *System sizes and test results*

System	A	B	C	D
Storage tank volume (m^3)	0.27	0.27	0.27	0.20
Collector surface area (m^2)	2.98	1.66	3.13	3.13
Total no of tubes/pipes	20	16	30	30
Area/volume (m^2/m^3)	11.03	6.15	11.59	15.65
Max temperature achieved with no draw-off (°C)	65	50	100	>84
Overnight temperature drop with no draw-off (°C)	2–6	1-3.5	2–11	2.5–6.5
Daily system efficiency at $\Sigma H = 4.5$ kW/m^2 (%)	47.6	31.4	65.8	40.8
Daily water temp. rise at $\Sigma H = 4.5$ kW/m^2 (°C)	20.6	7.6	29.9	25.0
Expected daily water temperature rise at $\Sigma H = 4.5$ kW/m^2 adjusted for area/volume ratio = 11.03 (°C)	20.6	13.6	28.4	17.6

Figure 3. *U-tube and heat pipe solar water heaters set-up.*

For the horizontal tanks, nine Cu-con (Type T) thermocouples with an accuracy of ±0.5°C were inserted into each of the storage tank via three-probe tubes as shown in Figure 4. Each probe tube held three thermocouples spaced equally apart to determine the vertical water temperature distribution in the tank. For the vertical tank, five central probes were used. Ambient temperature was measured with a Cu-con thermocouple located nearby in the shade. Solar radiation was measured with a Kipp & Zonen solarimeter and integrator with an accuracy of ±2%. All temperatures and solarimeter outputs were connected to a data logger and continuously logged.

4.2 Water temperature distribution in a storage tank

A typical water temperature distribution in a horizontal storage tank is shown in Figure 5. For the horizontal tank, average water temperatures at each particular level were calculated by taking the arithmetic mean of the three probes at the same tank level. Overall mean water temperature ($\overline{T}$) was calculated by taking the arithmetic mean of all the nine probes. For the vertical tank, mean water temperature was calculated from the arithmetic mean of the five probes. At the start of the experiment, the water in the tank was at a uniform initial temperature. As the day progressed, temperature stratification within the tank could be clearly observed. As expected, the highest temperature occurred at the top of the tank. The temperature distribution was very nearly uniform from the middle of the tank to the top in the afternoon. Average bulk temperatures were determined by measuring the total area under the temperature–height distribution curve and compared with the arithmetic means. Bulk temperature differed from the arithmetic mean by less than ±0.3°C at most.

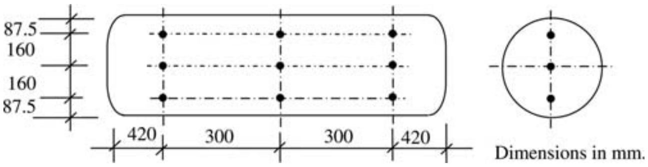

Figure 4. *Locations of thermocouples in a horizontal storage tank.*

4.3 Long-term system performance tests

The storage tanks were initially filled with water and the system left alone to be heated up for several days without any water draw-off. The mean water temperature in the storage tank ($\overline{T}$), ambient temperature (T_{amb}) and instantaneous total solar radiation intensity (H) were plotted hourly over the entire test period of several days. Accumulated daily total solar radiation was noted every 24 h from midnight. Systems B, C and D were tested side by side simultaneously over the same period. Typical results obtained for these three systems are shown in Figure 6. The weather experienced during the 6 days of testing varied from hot on day 4 when daily total solar radiation recorded was ~5.65 kWh/m^2 to cloudy on day 2 with ~2.15 kWh/m^2. Ambient temperature varied from ~38°C during the day to ~24°C at night. As noted in Table 1, the maximum mean storage water temperature attained with the U-tube collector system B was about 50°C. The maximum temperature for the natural convection heat pipe system C reached up to nearly 100°C. For the force convection system D, the maximum temperature was observed to be increasing and reached up to 84°C. In the present system D, the circulation pump was controlled to stop pumping at a collection temperature of ~90°C as a safety precaution. Hence it would not be possible for this system to attain more than 90°C under the present situation. From the previous results, the flat-plate system A attained ~65°C. The natural convection heat pipe system C provided the highest long-term temperature. The

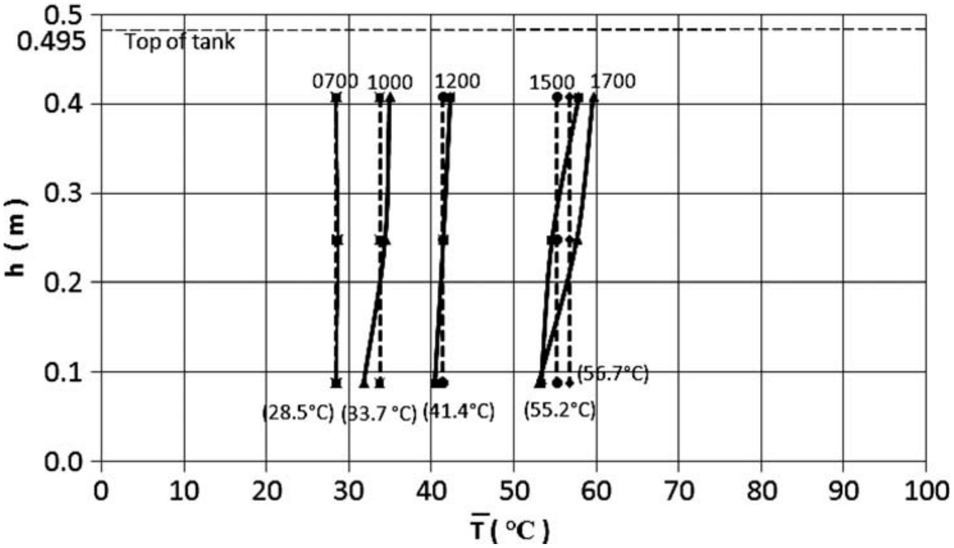

Figure 5. *Typical water temperature distribution in a horizontal storage tank.*

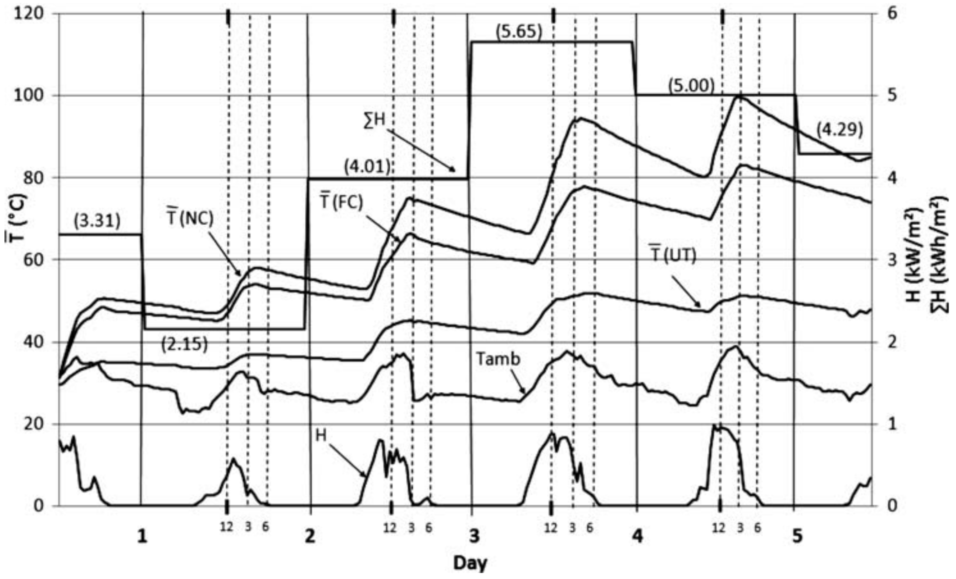

Figure 6. *Long-term performance of the heat pipe and U-tube SWHs without water draw-off.*

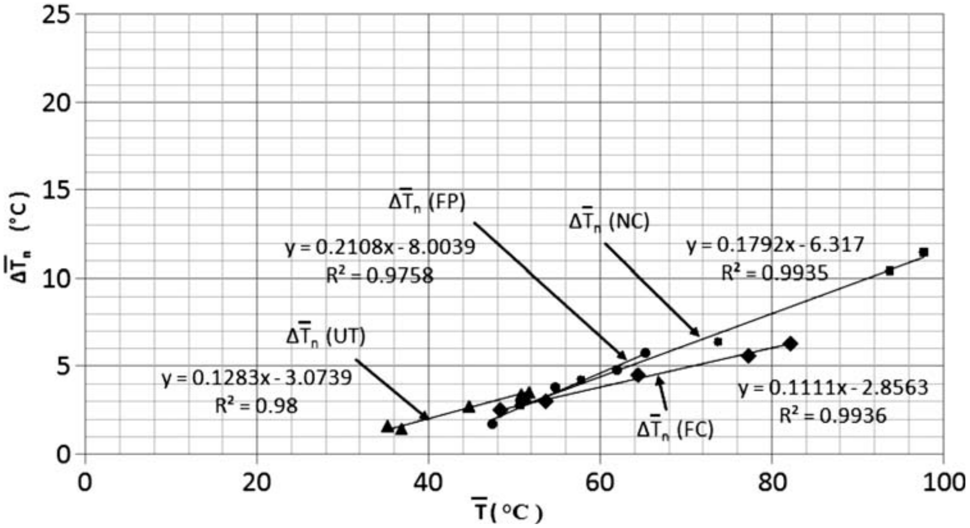

Figure 7. *Overnight temperature drops without water draw-off.*

maximum water temperature for the U-tube system B was low because the collectors were placed in a vertical position. The amount of direct solar radiation on the surface was thus very much reduced under Malaysian weather conditions.

The overnight temperature drop ($\Delta\overline{T}_n$) for systems B, C and D from 6 p.m. to 7 a.m. the next morning can be obtained from the long-term performance tests of Figure 6. The results are shown in Figure 7. As expected, the overnight temperature drop is greater, the higher the initial storage temperature ($\overline{T}_{5\text{p.m.}}$) in the tank. The overnight water temperature drop ranged from ~2–6°C for the flat-plate system, 1–3.5°C for the U-tube system, 2–11°C for the natural convection heat pipe system and 2.5–6.5°C for the force convection heat pipe system. It should be pointed here that the capacities and insulation qualities of the horizontal and vertical tanks are different natural and force convection heat pipe systems. Also, reverse flow is eliminated in the latter due to the pump not operating at night. For all cases, overnight losses due to both standing tank losses and reverse flow were not isolated.

4.4 Daily performance tests

The system was completely drained in the evening around 5 p.m. local time and left overnight. The temperature of the water in the storage tank ($\overline{T}$), ambient temperature (T_{amb}), instantaneous solar radiation intensity (H) were recorded hourly. The process of draining and refilling the tank was repeated and tests were carried out over a period of several

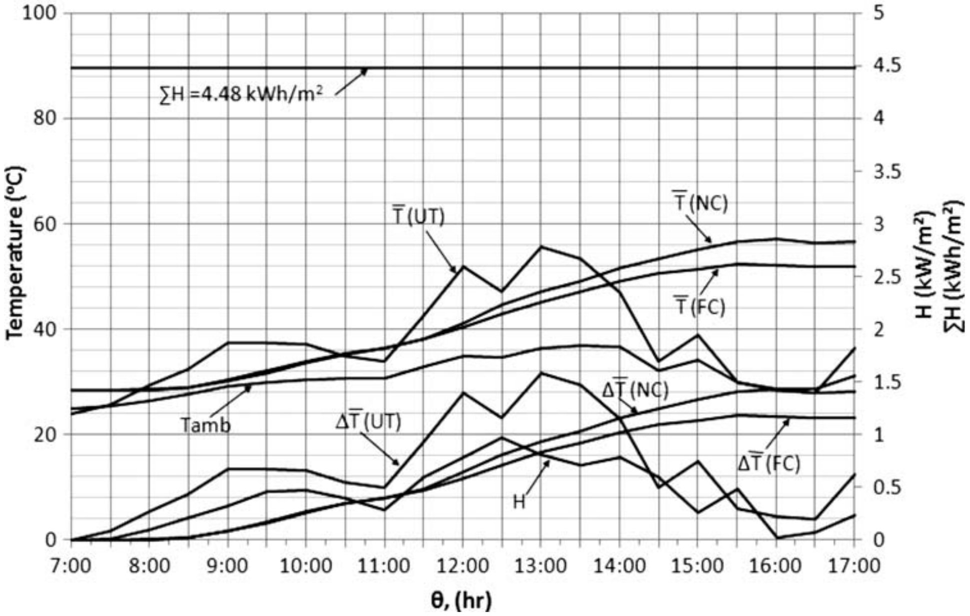

Figure 8. *Typical daily performance of the heat pipe and U-tube SWHs with water draw-off at end-of-day.*

days. Accumulated daily total solar radiation was noted every 24 h from midnight. A typical daily performance of systems B, C and D is shown plotted hourly in Figure 8. Mean water temperature increases as the day progressed. For the flat plate and heat systems [A, C and D], it was observed that the water temperature remained quite steady towards the evening and starts to drop off after 5 p.m. For the U-tube system [B], it was observed that the water temperature started to drop off as early as around 1 p.m. This was because the U-tube solar collectors were placed vertically and could only manage to collect the diffuse portion of the incident radiation.

The mean end-of-day system efficiency is defined as:

$$\overline{\eta} = \frac{\rho \ V \ c_p \Delta\overline{T}}{A \ \sum H} \times \ 100\% \tag{1}$$

where ρ is the density of water (kg/m^3), V the volume of the storage tank, c_p the specific heat of water (kJ/kg k), $\sum H$ the accumulated total solar radiation intensity (kWh/m^2), A the collector surface area (m^2) and the end-of-day temperature rise is calculated from

$$\Delta\overline{T} = \overline{T}_{5\text{p.m.}} - \overline{T}_{7\text{a.m.}} \tag{2}$$

Figure 9 compares the end-of-day mean water temperature rise ($\Delta\overline{T}$) and mean system efficiency ($\overline{\eta}$) at 5 p.m. for all four systems tested. As mentioned earlier, system A was tested a few months before systems B, C and D were tested. As expected, the mean water temperature rise increased as solar radiation increased. On an average day with ~4.5 kWh/m^2 of radiation, the mean water temperature rise would be ~21°C for the flat plate (A), 8°C for the U-tube (B), 30°C for the natural convection heat pipe (C) and 25°C for the force convection heat pipe (D) system. The results showed that the natural convection heat pipe system had the highest system efficiency among the systems tested followed by the flat-plate system.

The mean water temperature rise and hence the end-of-day water temperature depend upon the collector area/storage tank volume ratio of the system. A large area/volume ratio would result in a higher temperature rise. The mean system efficiency results would take this into account. Table 1 shows the system area/volume ratio for the four systems tested. Performance results could be pro-rated according to this ratio for each of the individual system. For an average day with 4.5 kWh/m^2 of radiation, the pro-rated expected mean water temperature rise could be calculated from Equation (1), viz,

$$\Delta\overline{T} = \frac{\overline{\eta}\sum H}{100\rho c_p}\left(\frac{A}{V}\right) \tag{3}$$

Table 1 shows that by pro-rating all the results to the same area/volume ratio (=11.03) as the flat-plate system A, the expected water temperature rise of the U-tube system (B) was 13.6°C, the natural convection heat pipe (C) 28.4°C and the force convection heat pipe system (D) 17.6°C. The natural convection heat pipe system (C) performed better than the force convection system (D) because of the heat exchanger efficiency penalty in the latter. The natural convection heat pipe system (C) performed better than the flat-plate system (A), showing that the double glass evacuated tube and selective surface of the heat pipe was better. The U-tube system (B) had a poor performance because the vertical collector was exposed to the Sun at a vertical angle and in Malaysia, the Sun is nearly always overhead. However, it managed to provide hot water at 41.6°C (assuming starting cold water temperature is at 28°C) which is

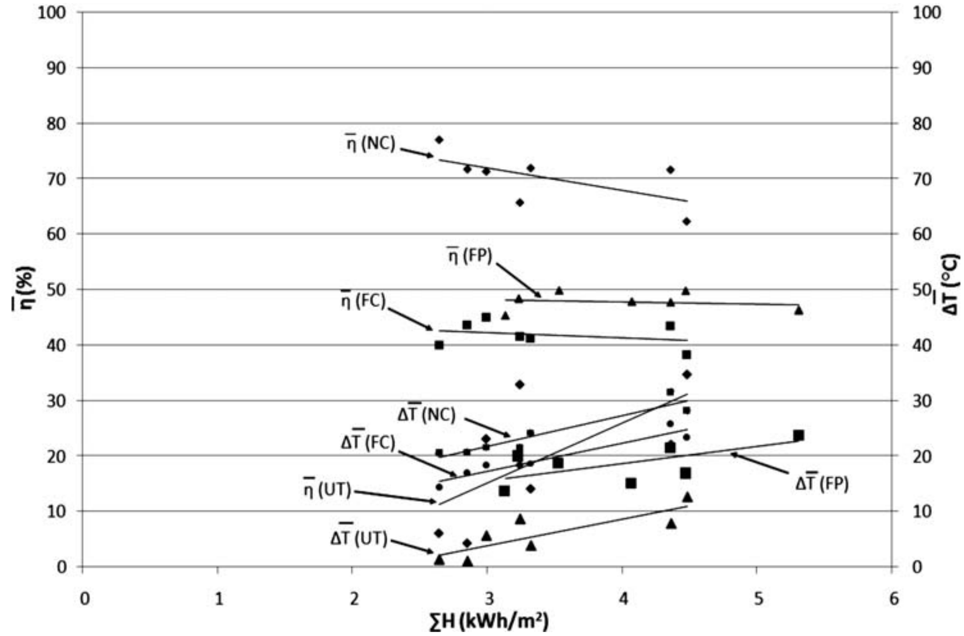

Figure 9. *End-of-day comparative performance with water draw-off.*

sufficient for bathing purposes. It could also be easily mounted in balconies of high-rise apartments where the others could not. The above demonstrates the effectiveness of the performance test procedure proposed.

5 CONCLUSION

A performance test procedure whereby the performance of SWHs which are tested on different days was compared as if they were simultaneously tested side by side was presented. In order to evaluate the procedure, four SWH systems tested on different days were presented and compared. Three of these, the tube-in-fin flat plate, U-tube and heat pipe types, were all under natural convection. The fourth system was the heat pipe type under forced convection. The best performer was the natural convection heat pipe system where the maximum temperature reached up to nearly 100°C. Next, the force convection heat pipe system achieved 84°C followed by the flat-plate system at 65°C and the U-tube system at 50°C. Overnight temperature drops due to standing tank loss and reverse flow were presented in terms of initial tank temperature. By prorating all the results to reflect on the same area/volume ratio (=11.03) as the flat-plate system, the expected water temperature rise of the U-tube system would be 13.6°C, natural convection heat pipe system, 28.4°C, and the force convection heat pipe system, 17.6°C. The U-tube system had the poorest performance because of the vertical inclination of the collectors which reduced their exposure to solar radiation in Malaysia. The forced convection heat pipe system suffered in terms of the penalty paid because of the heat exchanger in the system.

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