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A fast response heat pump water heater using thermostat made from shape memory alloy

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Abstract

The heat pump water heater produces hot water so slow at low ambient temperature that it frequently could not meet the hot water load demand in winter. The present study develops a fast response heat pump water heater (FRHP) designed with two separate tanks (supply and holding tank) which are connected by a thermostat made from shape memory alloy (SMAV). The SMAV is a mechanical heat-sensitive device made from shape memory alloy which keeps the valve closed when the water temperature is not high enough. This will isolate the tanks and let the vapor compression cycle heat up the supply tank only. The speed of temperature rise thus is increased. The SMAV will open and induce a natural circulation between two tanks to transfer the heat from the supply tank to the holding tank, when water is heated to a designated temperature. A 100 l FRHP was built and tested in the present study. The experimental results showed that the temperature response speed of the supply tank, before SMAV is opened, reaches 1.056 °C/min and the holding tank, after SMAV is opened, reaches 0.828 °C/min at ambient temperature 20 °C. The FRHP will heat up 50 l water in the supply tank with 30 °C temperature rise within 40 min in winter which is acceptable in domestic application. The energy consumption is in the range 0.008–0.016 kWh/l of hot water at about 55 °C.
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Keywords: Heat pump; Solar energy; Water heater; Air-source heat pump

1. Introduction

The domestic heat pump water heater is basically an air-source heat pump utilizing Rankine cycle to extract heat from ambient air at coefficient of performance (COP) higher than 2.0 and thus could save a lot of energy. National Taiwan University has been devoted to the development of integral-type solar-assisted heat pump water heater (ISAHP) since 1997. Several types of ISAHP with different structures were designed and tested. Huang and Chyng [1] first proposed the design of ISAHP. The ISAHP was composed of a Rankine or vapor compression cycle coupled with a solar collector that acts as an evaporator. Both solar and ambient air energies were absorbed at evaporator and pumped to storage tank via the Rankine cycle. Furthermore, ISAHP integrated the heat pump, solar collector, and water storage tank together to come up with a single unit that is easy to install. Huang and Chyng [2] designed the ISAHP to operate at evaporator temperature lower than ambient temperature. The measured COP for the ISAHP lay in the range 2.5–3.7 at water temperature between 25 and 61 °C. Chyng et al. [3] also developed a method of analysis of an ISAHP. Huang and Lee [4] showed that the average energy consumption of ISAHP was 0.019 kWh l hot water at 57 °C from the long term experiment. This is much lower than the electric water heater, around 0.06 kWh/l, and conventional solar water heater which uses electric backup heater, 0.02–0.05 kWh/l. Huang et al. [5] designed a heat-pipe enhanced solar-assisted heat pump water heater (HPSAHP) which was operated in the heat-pump mode when solar radiation was low. Also, HPSAHP could operate without electrical

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Nomenclature

A_C	inner across area of storage tank, m^2
B_0 and B_1	flow resistance parameters in Eq. (9)
C_p	specific heat of water, kJ/kg °C
D	inner diameter of storage tank, m
dT/dt	temperature response speed of supply tank, °C/s
$d\theta/dt$	temperature response speed of holding tank, °C/s
H	height of storage tank, m
H_{th}	thermosyphon pressure head, m H_2O
H_f	flow resistance, m H_2O
K_f	heat conduction coefficient of water, kW/m °C
M	mass of water in the storage tank, kg
$\dot{m}$	mass flow rate of natural circulation loop, kg/s
$\dot{m}_L$	mass flow rate of hot water load, kg/s
N	number of stratified layer
SW	specific weight of water
T	water temperature in the supply tank, °C
T_a	ambient temperature, °C
T_e	outlet water temperature, °C
T_i	inlet water temperature, °C
T_H	water temperature of natural circulation loop from supply tank to holding tank, °C
T_w	water temperature, °C
t_f	total time duration for discharging the water, s
U	heat transfer coefficient, kW/m^2 °C
Q	heating rate, kW
z	vertical distance, m
α_{1i}, α_{Ni}, β_{1i}, β_{Ni}, ε_{1i} and ε_{Ni}	control functions in Eqs. (1) and (2)
η	hot water discharge efficiency
θ	water temperature in the holding tank, °C
θ_L	water temperature of natural circulation loop from holding tank to supply tank, °C
ν	kinematic viscosity of water, m^2/s

Subscripts

h	holding tank
i	ith section of water in the storage tank
init	initial
s	hot water supply tank

consumption during high solar radiation period using heat-pipe mode to save more energy.

The heat pump water heater seems to be a promising energy-saving device. However, the slow temperature response speed in cold weather results in the design of a large water storage tank in order to deal with the peak hot water load. Some commercial heat pump water heater is designed with 250 l storage tank or larger. Hence, it is difficult to install in houses with limited space. This is one of the reasons that hinder the dissemination of the heat pump water heater. The development of a fast response heat pump water heater is thus quite necessary.

The present study intends to develop a fast response heat pump water heater (FRHP). FRHP is designed with two separate tanks (supply and holding tank) which are connected by a thermostat or thermal valve made from shape memory alloy (SMAV). The SMAV is a mechanical heat-sensitive device made from shape memory alloy which keeps the valve closed when the water temperature is not high enough. This will isolate the two tanks and let the vapor compression cycle heat up the supply tank only. The speed of temperature rise thus is increased. The SMAV will open and induce a natural circulation between two tanks to transfer the heat from the supply tank to the holding tank, when water is heated to a designated temperature. The present study was carried out to show the feasibility of this novel heat pump water heater.

2. Prototype design

The schematic diagram of fast response heat pump water heater (FRHP) with shape memory alloy valve (SMAV) is shown in Fig. 1. The FRHP prototype was designed in two tanks and the volume of each tank was 50 l. The water storage then consists of a hot water supply tank where the heating device (condenser) was immersed and a holding tank which was used to store the hot water. No auxiliary electric heater is needed in FRHP.

The FRHP was designed based on the principle of Rankine cycle, the same as the ISAHP. A R22 rotary-type compressor with 14.8 cc per revolution and 1 kW rated input power was used. The condenser heat exchanger was design in coiled tube which was immersed in the supply tank. The evaporator was a fan coil with 4.3 kW maximum heat transfer. The design specifications are listed in Table 1. The overall dimension of the prototype is H1600 × W800 × D500 mm.

The SMAV is a mechanical heat-sensitive device made from shape memory alloy. The mechanism of SMAV is shown in Fig. 2. The shape memory alloy is made in spring form which will shrink and open the valve when it is heated up to certain temperature. When the temperature decreases to a particular value, the SMAV is closed.

The operation of the SMAV can be determined by measuring the water flow resistance (pressure drop divided by flow rate) through the valve at different water temperatures. The results are shown in Fig. 3.

The experiment was carried out with water temperature lower than 45 °C during which the SMAV is closed. As the water (or shape memory alloy) temperature increases to about 50 °C, the hydraulic resistance decreases rapidly and reaches a constant at very low value. This indicates that the SMAV is opened at temperature >50 °C in a heating process. In a cooling process from 58 to 45 °C, the

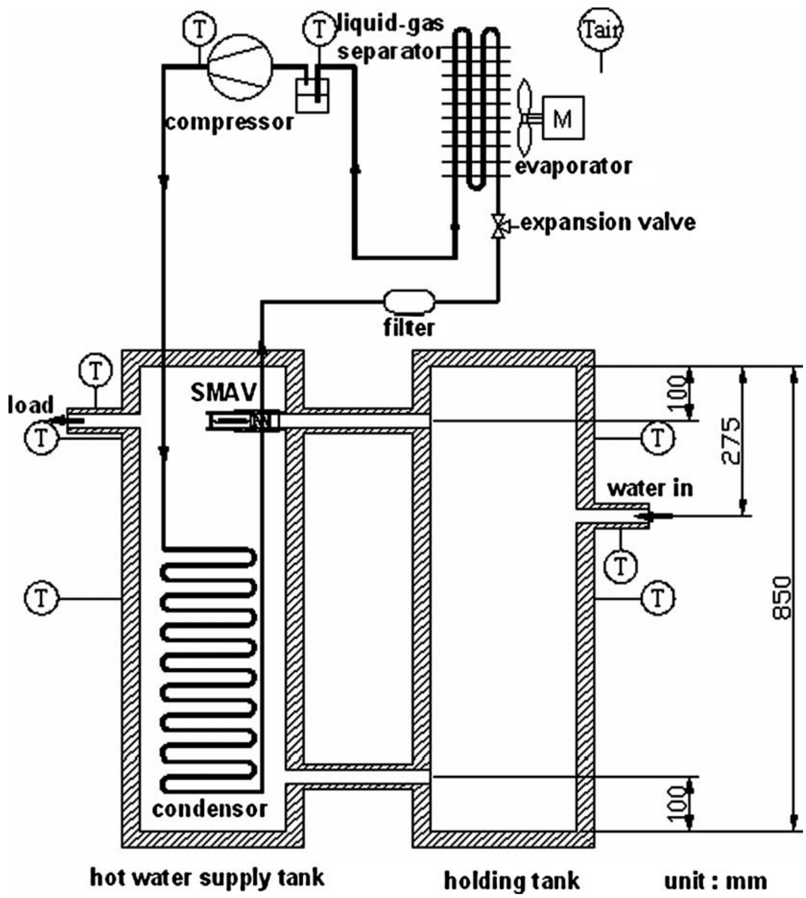

Fig. 1. Schematic diagram of the FRHP.

Table 1
Specifications of the FRHP components

Component	Specification
Compressor	R22, 1 kW/ 220 V, 14.8 cc/rev.
Condenser	Bare copper tube, diameter 9.5 mm, length 30 m
Expansion valve	Capillary tube, diameter 3 mm, length 90 cm
Evaporator	Fan-coil, maximum transfer rate 4.3 kW
Liquid–gas separator	Stainless tank, diameter 10 cm, height 21 cm
Supply/holding tank	50 l, diameter 27 cm, height 85 cm

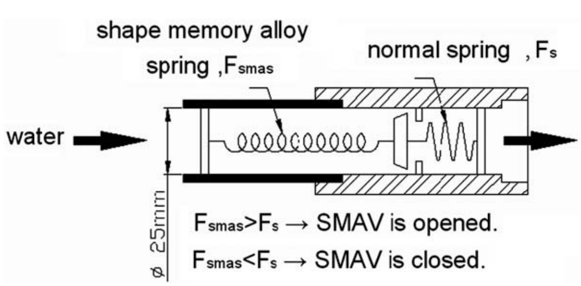

Fig. 2. Design of shape memory alloy valve (SMAV).

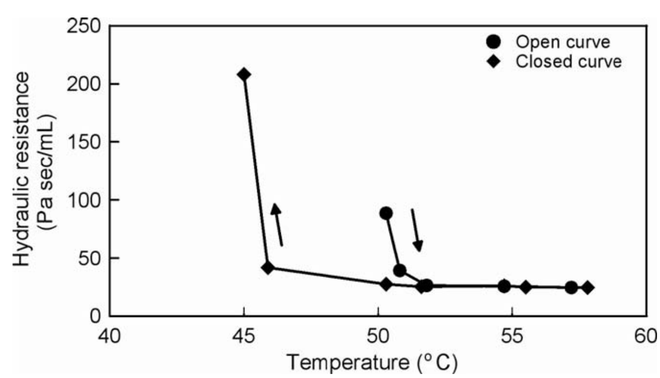

Fig. 3. Hydraulic resistance variation of SMAV.

hydraulic resistance increases rapidly around 46 °C and the SMAV is closed at temperature lower than 46 °C which is denoted as the close temperature of the SMAV. There is a hysteresis in valve open and close temperatures. That is, once the SMAV is opened at 50 °C in heating process, it will close again at 46 °C. For the application of SMAV in FRHP, this means that the supply tank will be isolated before the water temperature reaches 50 °C and the heat pump will heat the supply tank only at faster speed. Once the SMAV is opened at 50 °C, the hot water at the top of the supply tank starts to flow into the holding tank via natural circulation. The cold water at the bottom of the holding tank flows into the supply tank.

3. Experiment setup

A FRHP was built in the lab. To measure the performance, nine T-type thermocouples with uncertainty of ±0.7 °C were installed on the locations indicated in Fig. 1.

The ambient temperature and the temperature at the discharge and suction ports of the compressor are measured. The temperature distribution of the supply tank and the holding tank were measured by four thermocouples. Two thermocouples were installed at one-eighth and half of the supply tank height from the top. In the holding tank, another two thermocouples were installed at the same level. Another two thermocouples were installed at the inlet and outlet of the dual-tank to measure the inlet and outlet water temperature. The total power input to the system was measured by a wattmeter within ±1.5% uncertainty. A hybrid recorder (YOKOGAWA DR130) was used for data acquisition.

4. Analysis of natural circulation between two tanks

In order to predict the natural circulation between the supply and the holding tank when SMAV is opened, we develop a simulation program using the thermal stratification model developed by Close [6]. This model has been successfully used in solar collector and ISAHP analysis [3,7]. Close's model is thus used in the present study to predict the temperature response in the tank. The tank is divided into N well mixed sections. Applying energy balance to the ith section and heat conduction between two adjacent sections, we obtain a series of differential equations for a tank.

Hot water supply tank:

$$\left(\frac{MC_p}{N}\right)_s \frac{dT_i}{dt} = \frac{Q}{N} + \left(\frac{U\pi DH}{N}\right)_s (T_a - T_i) + (K_f A_c N/H)_s[\varepsilon_{Ni}(T_{i+1} - T_i) + \varepsilon_{1i}(T_{i-1} - T_i)] + \alpha_{1i}\dot{m}C_p(\theta_L - T_i) + \alpha_{Ni}C_p(T_{i-1} - T_i) \quad (1)$$

Holding tank:

$$\left(\frac{MC_p}{N}\right)_h \frac{d\theta_i}{dt} = \left(\frac{U\pi DH}{N}\right)_h (T_a - \theta_i) + (K_f A_c N/H)_h[\varepsilon_{Ni}(\theta_{i+1} - \theta_i) + \varepsilon_{1i}(\theta_{i-1} - \theta_i)] + \beta_{1i}\dot{m}C_p(T_H - \theta_i) + \beta_{Ni}C_p(\theta_{i+1} - \theta_i), \quad (2)$$

where Q is heating rate; M is the mass of water in the storage tank; $\dot{m}$ is the mass flow rate of natural circulation loop between the two tanks; subscript s and h denote supply tank and holding tank, respectively. dT_i/dt is the temperature response speed in the ith section of the hot water supply tank; $d\theta_i/dt$ is the temperature response speed in the ith section of the holding tank; θ_L is water temperature of natural circulation loop from holding tank to supply tank; T_H is water temperature of natural circulation loop from supply tank to holding tank. $\varepsilon_{1i} = \varepsilon_{Ni} = 1$ for $i = 2, 3, \ldots, N-1$. α_{1i}, α_{Ni}, β_{1i}, and β_{Ni} are control functions defined as follows:

$$\alpha_{1i} = \begin{cases} 1, & \text{if } T_{i-1} < \theta_L < T_i \\ 0, & \text{other} \end{cases} \quad (3)$$

$$\alpha_{Ni} = \dot{m}\sum_{j=1}^{i-1} \alpha_{1j} \quad (4)$$

$$\beta_{1i} = \begin{cases} 1, & \text{if } \theta_i < T_H < \theta_{i+1} \\ 0, & \text{other} \end{cases} \quad (5)$$

$$\beta_{Ni} = \dot{m}\sum_{j=i+1}^{N} \beta_{1j}. \quad (6)$$

When the SMAV opens, the natural circulation is induced and transfers the heat from the supply tank to the holding tank. The circulating flow rate depends on the water temperature variations in the tanks. The water temperature distribution in the tank can be evaluated by solving Eqs. (1) and (2). The thermosyphon pressure head H_{th} which is the driving force of the natural circulation is defined as follows:

$$H_{th} = \int [SW(\theta) - SW(T)]dz, \quad (7)$$

where SW is the specific weight of water that can be approximated by the relation:

$$SW(T_w) = -4.05 \times 10^{-6}T_w^2 - 3.906 \times 10^{-5}T_w + 1.000256. \quad (8)$$

The thermosyphon head H_{th} generated is used to overcome the flow resistance of the water circulation that is caused by wall friction and other losses in the loop. The following quadratic function can be approximated to describe the loop flow resistance [7]:

$$H_f = B_0 v\dot{m} + B_1\dot{m}^2, \quad (9)$$

where v is the kinematic viscosity of the water, defined as follows:

$$v(T_w) = \frac{1}{2.1482\{(T_w - 8.435) + [8078.4 + (T_w - 8.435)^2]^{1/2}\}} \quad (10)$$

The coefficients B_0 and B_1 can be determined experimentally by directly measuring the variation of flow resistance with mass flow rate. The result is shown in Fig. 4, which gives $B_0 = 3.191 \times 10^5$ s^2/kg m and $B_1 = 8.702$ s^{2}m/kg^2. Combining Eqs. (7) and (9), the governing equation for the momentum balance equation of the natural circulation loop is

$$\int [SW(\theta) - SW(T)]\, dz = B_0 v\dot{m} + B_1\dot{m}^2. \quad (11)$$

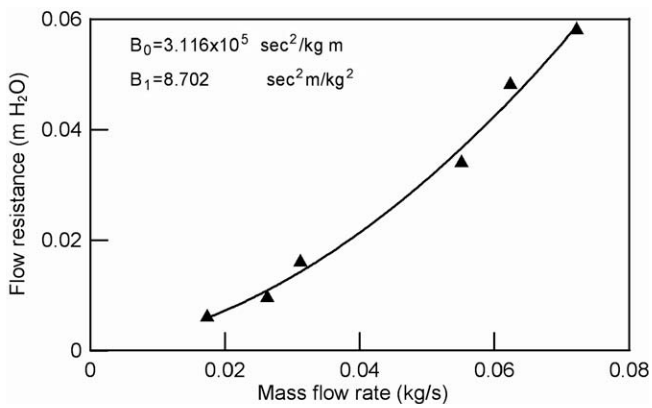

Fig. 4. Flow resistance measurement of natural circulation loop.

The temperature response speed of supply tank and holding tank thus can be predicted using Eqs. (1), (2) and (11).

5. Experimental results

The FRHP was tested indoor. The FRHP is installed in an environmental chamber to simulate different ambient temperature. A preliminary test for adjusting the refrigerant charge of FRHP was done first. The performance test then follows, including measuring the transient temperature variation inside the two tanks, the temperature response speed and hot water discharge efficiency from the storage tanks. The average water temperature taken from the two thermocouples inside each tank was used to represent the tank temperature.

5.1. Performance test for heating without hot water load

Fig. 5 shows the heating performance of FRHP without hot water load at ambient temperature around 20 °C. The initial average water temperature is 21 °C. Once the FRHP is started, the supply tank is heated as priority while the SMAV is closed for isolating the tank so as to double the temperature response speed. When the water temperature of the supply tank reaches the designed value, the SMAV starts to open and allows hot water to flow into the holding tank via natural circulation. During this period, the temperature response speed of the supply tank was 1.056 °C/min. This indicates that the supply tank with 50 l water can be heated up to 50 °C from 21 °C within 27 min. The circulating flow rate depends on the water temperature variations in the dual-tank. The finial temperature of holding tank was set 50 °C at which point the operation was terminated. The holding tank was heated from 21 to 50 °C and temperature response speed of the holding tank was 0.828 °C/min. On the other hand, the temperature response speed of the supply tank was 0.348 °C/min.

The total heating time for total 100 l water was about 60 min from startup. After FRHP was shut down, the natural circulation loop still transfers the heat from the supply tank to the holding tank since dual-tank has not reached a thermal equilibrium. About 40 min later, the water temperatures of the supply tank and the holding tank were 55 and 53 °C, respectively. Fig. 6 shows the temperature of the vapor compression cycle.

The FRHP was tested under different ambient temperatures to determine the energy consumption in making hot water. Fig. 7 shows that the electricity consumption per liter of hot water around 50 °C at different ambient temperature (6–38 °C) ranges from 0.008 to 0.016 kWh/l. As compared to electric heater (0.06 kWh/l), a lot of energy is saved using FRHP. The electricity consumption per liter of hot water decreases almost linearly with ambient temperature.

Heat pump produces hot water at lower speed during cold weather. Experiments were thus carried out to determine the temperature response speed of the supply tank at different ambient temperature. The supply tank is heated with SMAV closed.

We also used the aforementioned tank model to predict the temperature response speed of the supply tank at the same operating condition. The experimental results show that the temperature response speed of supply tank lies in the range 0.714–1.234 °C/min for different ambient

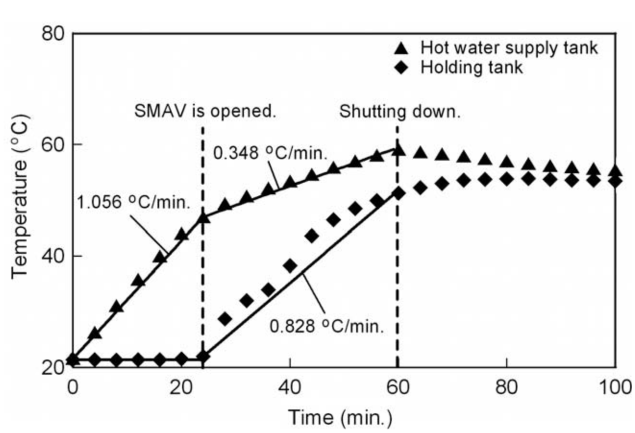

Fig. 5. Performance of FRHP at ambient temperature 20 °C.

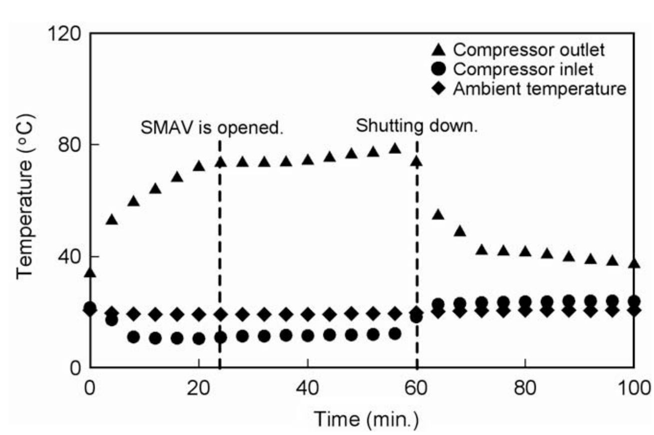

Fig. 6. Performance of vapor compression cycle at ambient temperature 20 °C.

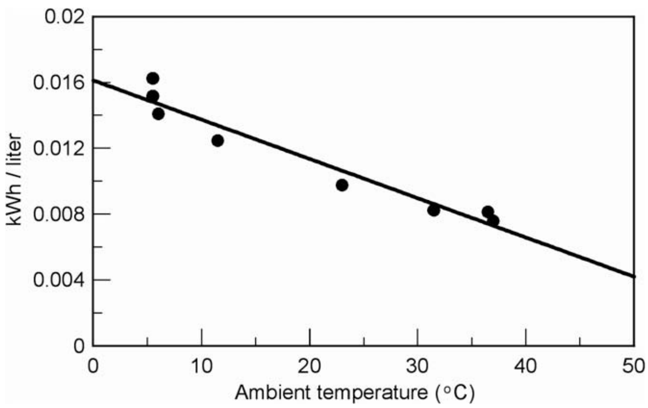

Fig. 7. Electricity consumption at various ambient temperature.

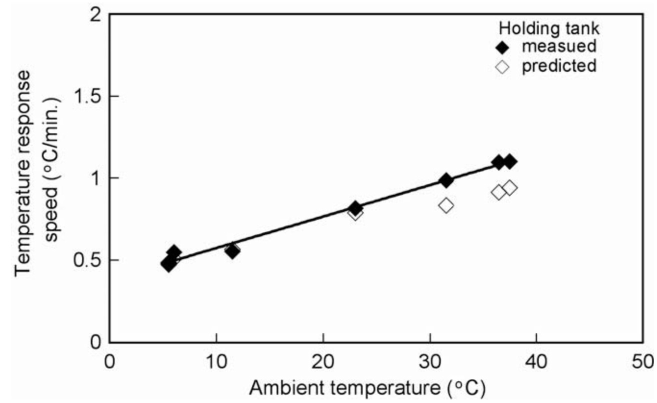

Fig. 9. Comparison between the measured and predicted temperature response speed of holding tank.

temperature, as shown in Fig. 8. The temperature response speed of supply tank increases almost linearly with increasing ambient temperature. The predicted results using energy balance method are consistent with the measured value.

When water temperature of supply tank reaches the designed value, the SMAV opens and the heat is transferred from the supply tank to the holding tank via natural circulation. The holding tank was heated from 22 to 50 °C. During this period, the temperature response speed of the holding tank was measured under various ambient temperatures. Similarity, we examined the temperature response speed of holding tank for the same operating condition. The experimental results show that temperature response speed of the holding tank lies in the range 0.483–1.1 °C/min for different ambient temperature, as shown in Fig. 9. The trend in temperature response speed of holding tank with ambient temperature is similar to Fig. 8. However, temperature response speed of holding tank is slightly slower than that of the supply tank shown in Fig. 8. This is reasonable since the supply tank was also heated simultaneously. The predicted results are very close to the measured data.

It also shows that at ambient temperature 10 °C, the temperature response speed of the supply tank is 0.8 °C/min. This means that the FRHP will heat up 50 l water with 30 °C temperature rise within 40 min. This is acceptable for domestic application since a single user may take about half an hour to consume about 50 l hot water for bath and the water usage may not be always continuously.

5.2. Performance test for heating with hot water load

It is important to know the hot water supply capability of the FRHP. The FRHP thus allows a hot water withdraw at 3 l/min right after the water temperature of the supply tank reaches 45 °C with SMAV still closed. The experimental results shown in Fig. 10 at ambient temperature around 20 °C and inlet water temperature at 21 °C indicates that the heat rejected from Rankine cycle is completely taken away by the discharging water. At steady state, the discharge water temperature is still higher than 40 °C. This indicates that the FRHP can continuously supply hot water to load at temperature 40 °C at inlet temperature 21 °C.

Similar test was also performed when the water temperature of the supply tank and the holding tank were 57 and 51 °C, respectively, with SMAV opened. The FRHP then allows a hot water load withdraw at 3 l/min. The experimental result is shown in Fig. 11 for ambient temperature

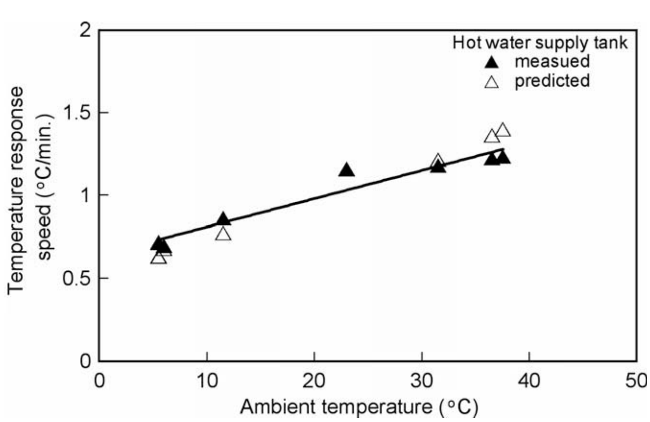

Fig. 8. Comparison between the measured and predicted temperature response speed of supply tank.

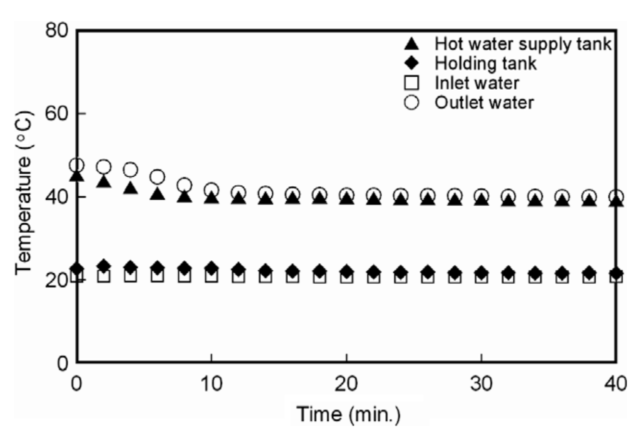

Fig. 10. Water temperature variations at hot water load 3 l/min.

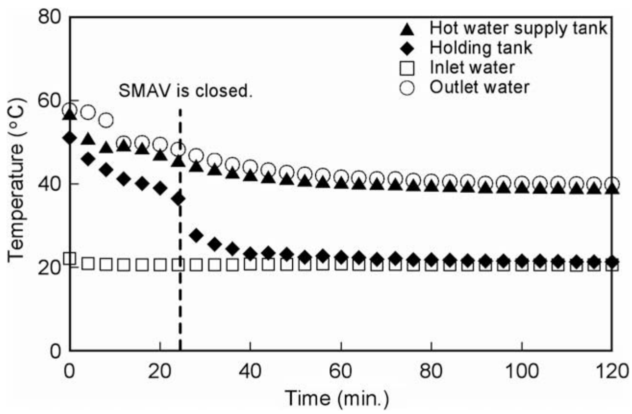

Fig. 11. Water temperature variations at hot water load 3 l/min.

around 20 °C. It is seen again that the discharge water temperature is still higher than 40 °C at steady state. The FRHP is shown again to be able to continuously supply hot water to load at temperature 40 °C at inlet temperature 21 °C.

5.3. Hot water discharge efficiency

Beside the internal mixing of hot water with inlet cold water during discharge, the use of SMAV may affect the hot water discharge capability. The test is to measure the total energy discharged from the storage tank, i.e. hot water discharge efficiency. The hot water discharge efficiency η is defined as follow [8]:

$$\eta = \frac{\int_0^{t_f} \dot{m}_L C_p [T_e(t) - T_i] dt}{(M_s + M_h) C_p [(T + \theta)_{init}/2 - T_i]}, \tag{12}$$

where $\dot{m}_L$ is the mass flow rate of hot water load; T_e is outlet water temperature; T_i is inlet water temperature; $t_f = (M_s + M_h)/\dot{m}_L$ is the total time duration for discharging the water at the same volume of the dual-tank; subscript init denotes initial.

The test result of the hot water discharge efficiency is shown in Fig. 12. The initial temperature of the dual-tank was 52 °C and the hot water load was 3 l/min. It is seen that the discharge efficiency of the present heat pump reaches 0.872 which is high as compared to the single storage tank design. The use of the SMAV does not decrease the hot water discharge efficiency.

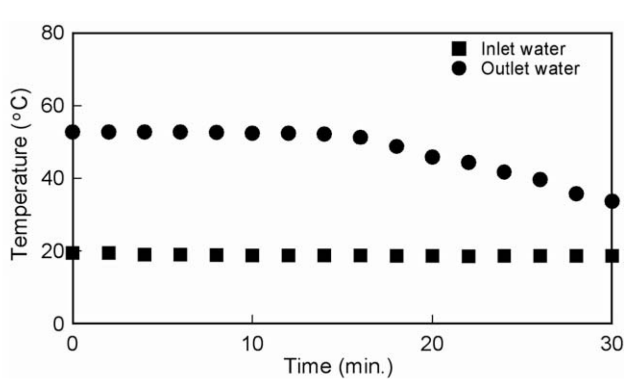

Fig. 12. Hot water discharging efficiency.

6. Discussions and conclusion

A fast response heat pump water heater (FRHP) with dual-tank inter connected by a shape memory alloy valve (SMAV) was designed and tested in the present study. The SMAV is a mechanical heat-sensitive device made from shape memory alloy which actuates the valve to open when it is heated up. The supply tank can be isolated by a SMAV to increase the temperature response speed. Some important results from the experiment are obtained and summarized as follows:

(1) FRHP does not need auxiliary electric heater to heat water at cold weather since it has a fast temperature response. At ambient temperature 10 °C, the temperature response speed of the supply tank is 0.8 °C/min. The FRHP will heat up 50 l water with 30 °C temperature rise within 40 min. This is acceptable for domestic application since a single user may take about half an hour to consume about 50 l hot water for bath and the water usage may not be continuously.
(2) The experimental results show that the temperature response speed of the supply tank, before SMAV opened, changes from 0.714 to 1.234 °C/min and the temperature response speed of the holding tank, after SMAV opened, changes from 0.483 to 1.1 °C/min, for the ambient temperature between 6 and 38 °C.
(3) The energy consumption of the FRHP lies in the range 0.008–0.016 kWh/l hot water at 55 °C. The heat pump developed in the present study is shown to be superior not only in the temperature response speed but also in the low energy consumption.
(4) The hot water discharging efficiency of FRHP reaches 0.872 which is higher than the single storage tank. The use of the SMAV does not decrease the hot water discharge efficiency.

Acknowledgements

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