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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.

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