NUMERICAL INVESTIGATION ON EFFECTS OF OPERATING PARAMETERS ON A NOVEL HEAT PIPE EMBEDDED ALUMINUM VENEER CURTAIN WALL SYSTEM

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Abstract- This paper describes a novel heat pipe embedded aluminum veneer curtain wall (HPeAVCW) system which integrates the aluminum veneer with heat pipes. Taking advantages of the heat pipe, most of the absorbed solar thermal energy by the outer aluminum sheet could be transferred to the cold flowing domestic water inside the embedded water box. Thus, the HPeAVCW system could generate domestic hot water and simultaneously reduce indoor heat gain or loss. Based on the heat transfer process, a mathematical model of the HPeAVCW system was firstly built. Then, the influences of key operating parameters, such as solar irradiation intensity and ambient temperature, together with the flow rate and temperature of the domestic feed water on the system thermal performance were assessed. The results quantified the level of influences of these parameters, in that high solar irradiation intensity and ambient temperature have positive effects on the system performance, while low inlet water temperature makes contribution to the water heat gain.

Index Terms- Aluminum veneer curtain wall, Heat pipe, Operating parameters analysis, System thermal performance

I. INTRODUCTION

Since the reserve of fossil fuels diminishes, the interest in utilizing solar thermal energy for hot water generation has been growing in recent years. Solar energy is environmentally clear and abundant and therefore, can be a promising alternative energy source to alleviate the energy-related and environmental problems. The development of solar water heater has been fast around the world. China, for example, achieved 1.50×108 m^2 of installed solar collector areas by 2010, and is targeting at 3.00×108 m^2 by 2020. This means annual growth rates of 13.6% by 2010, and 9.0% by 2020 [1]. Although the technology itself is mature, R&D work goes on to enhance collector efficiency through integration with other technologies, such as the heat pipe technology.

Heat pipe has high heat transfer efficiency and can transfer low-grade thermal energy to high heat flux, thus it has been applying extensively in different fields, such as air conditioning, solar water heating, waste heat recovery, etc. When heat flux comes to its evaporator section, the working fluid inside absorbs the heat and undergoes phase transformation from liquid to vapor. The vapor then transfers large amount of latent heat to the condenser section but only with a small temperature drop.

A large number of investigations on heat pipe-embedded solar collectors have been conducted. For example, Chow et al. compared the system performances of a single-phase open thermosyphon evacuated tube solar collector and a two-phase closed thermosyphon evacuated tube solar collector. The daily and annual thermal performance showed that the two-phase closed thermosyphon evacuated tube solar collector has better thermal performance than the single-phase open thermosyphon evacuated tube solar collector [2]. Through experimental and numerical studies, Wei et al. found that the maximum thermal efficiency could reach up to 66% when heat pipes are integrated with the flat-plate solar heat collector [3]. Mathioulakis et al. observed that the energy behavior of a heat-pipe type solar domestic hot water system could be up to 60% with wide temperature operating range and effective operation [4].

However, the vast majority of the solar collectors are roof-located. Additional installation space and structure are required for these solar water heater systems. This to certain extent has limited their application [5]. In recent years, the increase of high-rising building projects provides an excellent opportunity to opt for building integrated design. Several investigations have been carried out to integrate the solar heater with the exterior wall, such as the balcony-integrated micro-channel heat pipe evacuated tube solar collector-incorporated thermoelectric generation system and building integrated heat pipe embedded (BiHPe) wall system.

The micro-channel heat pipe evacuated tube solar collector-incorporated thermoelectric generation was proposed by Li et al. [6], which integrates the heat pipe evacuated solar collector with the thermoelectric (TE) energy converter. Also, this system uses the balcony wall-mounted method for installation, which takes advantages of the outer wall of buildings. Therefore, the system is not only able to generate domestic hot water and electricity simultaneously, but also to make perfect integration with the building façade. The numerical results illustrated that the micro-channel heat pipe evacuated tube solar collector-incorporated thermoelectric generation system has a high thermal performance and electricity production. However, the appearance of the building might be affected.

The BiHPe wall system studied by Chow et al. is able to solve the aesthetic problem [7]. In this system, an array of wickless heat pipes are welded on an absorber

plate and then embedded near the outer wall surface of the concrete wall structure. Thus, this system perfectly integrates with the building envelope. The heat energy absorbed in concrete is transferred via the heat pipe array to preheat the flowing domestic feed water in a fully enclosed water box at the top end. Accordingly, the solar thermal transmission through the wall reduces. For this reason, this system can simultaneously reduce the indoor heat gain/loss and generate domestic hot water (DHW). The thermal performance of the BiHPe system was evaluated experimentally and numerically, considering the various influencing design factors, i.e. heat pipe spacing, fin attachment, heat pipe location and configuration. For the annual thermal performance investigation, when BiHPe system applied in a hypothetical gym in Hong Kong, 76.1% indoor heat gain reduction can be achieved as compared to the reference bare concrete wall. The building with the BiHPe system reaps benefits from indoor heat gain/loss reduction and domestic water preheating energy saving. However, this is a well-known fact that the thermal conductivity of the concrete wall is much smaller than that of metal. Also, modern buildings prefer curtain wall of aluminum sheet which has aesthetic appearance and light weight. Therefore, the alternative application of BiHPe system to aluminum veneer curtain walling is expected promising.

Accordingly, a novel heat pipe-embedded aluminum veneer curtain wall (HPeAVCW) system has been proposed and studied. The mathematical model of the HPeAVCW system was firstly derived from physical laws, and then numerically solved by means of a self-developed Fortran program. The influences of the key operating parameters: solar irradiation intensity, ambient temperature, inlet domestic water mass flow rate and temperature, on the thermal performance of the HPeAVCW system were studied.

II. DESCRIPTION OF THE HPEAVCW SYSTEM

The layout of the novel HPeAVCW system is shown in Fig. 1. The cold domestic water from the supply main flows into the HPeAVCW system at fairly constant flow rate and temperature. When the inlet water temperature is lower than the temperature of the heat pipe condenser sections, the flowing domestic water is preheated. With the help of the auxiliary heater, the preheated domestic water is first stored in the water tank before supplying to users at the set temperature.

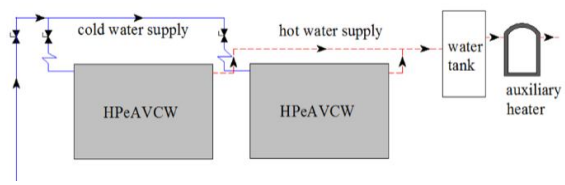


Fig. 1 Layout of the HPeAVCW system

Fig. 2 shows the facade details of the HPeAVCW, which consists of an outer aluminum sheet, a middle thermal insulation layer, an inner aluminum sheet, and an upper water box with flowing water inside. The evaporation sections of heat pipes are attached to the inner surface of the outer aluminum sheet with thermal conductive adhesive. Their condenser sections are immersed in the upper water box. The solar radiation falling on the outer surface of the curtain wall is partly reflected and partly absorbed. The majority of the absorbed solar radiation is then transferred to the DHW system. Thus, the HPeAVCW system may have good energy saving potentials without the compromise of building aesthetic appearance.

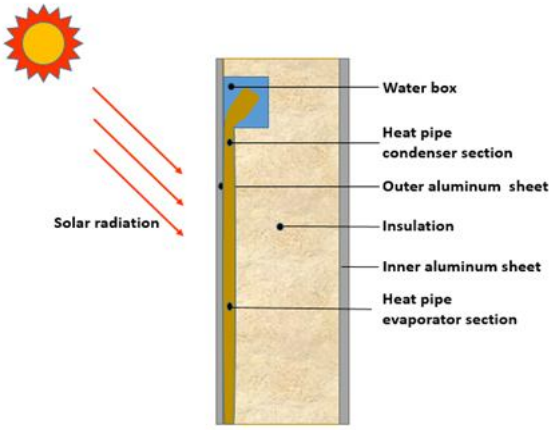


Fig. 2 Configuration of HPeCW system

III. NUMERICAL MODEL OF THE HEAT PIPE-EMBEDDED ALUMINUM VENEER CURTAIN WALL (HPEAVCW) SYSTEM

A. Physical model

In this study, the gravity assisted wickless heat pipe, one of the two-phase closed thermosyphon (TPCT), is employed. Considering that the heat pipe is to be integrated with the vertical wall, the wickless heat pipe owes excellent performances at this end, in comparison with the wicked heat pipe. The advantages lie in its simpler construction, smaller thermal resistance, wider operating limits, as well as lower manufacture cost.

The copper-water wickless heat pipes and the polished aluminum sheet are considered in this HPeAVCW study. Distilled water, which is nontoxic and cheap, was chosen as the working fluid. The heat pipes are positioned at a regular interval of 0.1m. The construction details are listed in Table 1. The indoor temperature is 25 °C in summer and 21 °C in winter.

Table 1 Design data of the HPeAVCW system

Construction	of 1.5 m length
curtain wall	1.2 m height
	3 mm thickness for aluminum veneer (outer layer)
	1.5 mm thickness for aluminum veneer (inner layer)
	50mm thickness for glass wool (middle layer)

Construction of wickless heat pipe	1000 mm evaporation sector 175 mm condenser section 30% liquid filling ratio 10 mm outer diameter of the evaporation section 8 mm inner diameter of the evaporation section 10 mm outer diameter of the condenser section 8 mm inner diameter of the condenser section

B. Mathematical model

The control-volume finite-difference method was employed in this study, in that a control volume of uniform properties and working conditions at any time instant can be represented by a single node in the simulation network [8]. The HPeAVCW system as shown in Fig.2 is represented by seven nodes: 'vo' for the outer aluminum sheet; 'e' for the evaporation section of the heat pipe; 'c' for the condenser section of the heat pipe; 'f' for the working liquid inside the heat pipe; 's' for the middle insulation layer; 'vi' for the inner aluminum sheet; and 'w' for the flowing water in the upper water box. Based on the energy balance, the mathematical model of the HPeAVCW system was built with the following assumptions and simplifications:

(1) The thermal capacity of any part of the HPeAVCW system is neglected when steady-state solutions are applied for all the energy balance equations;

(2)The contact thermal resistances between any two parts of the HPeAVCW system are neglected;

(3) The frame of the HPeAVCW system is well insulated without any heat loss to surroundings;

(4) Heat conduction along the longitudinal direction of heat pipe is neglected;

(5) The temperatures of each layer in each partition are considered to be equal;

(6) The solar irradiation of the outer panel surface is considered to be uniform.

C. Parameter definition

The system thermal efficiency η is used to assess the solar energy utilization capacity. This is calculated by a ratio of solar thermal energy transferred to DHW feed water to the incident solar energy on the outer surface of the aluminum veneer curtain wall, i.e.

$$\eta = \frac{Q_{water}}{I_0} \times 100\% \quad (1)$$

Where, Q_{water} is the flowing domestic water heat gain, W/m^2, $Q_{water} = c_w \dot{m}(T_{out} - T_{in})$; I_0 is the solar radiation intensity, W/m^2.

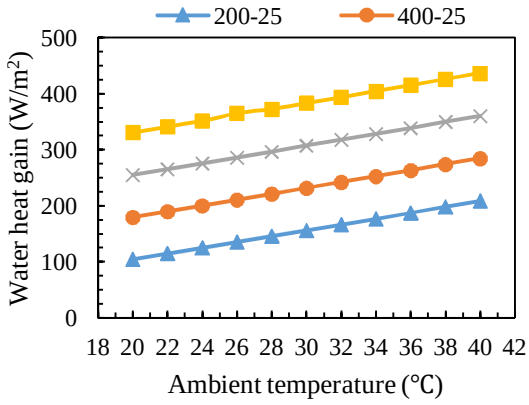
III. RESULTS AND ANALYSIS

The numerical simulations were carried out to quantify the influences of key operating parameters, including solar irradiation, ambient temperature, flow rate and temperature of inlet water of the water box on thermal performance of the HPeAVCW system, as well as to obtain optimal operating conditions for this system.

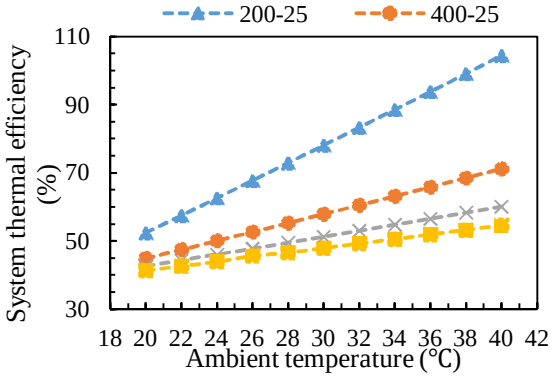
D. Effect of the outdoor weather condition on system thermal performance

The numerical results of the water heat gain Q_{water} and the system thermal efficiency η of the HPeAVCW system under different solar irradiation intensities and ambient temperatures are shown in Fig. 3 and 4.

As can be seen from Fig. 3(a) and Fig. 4(a), when solar irradiation intensity I_o keeps constant, water heat gain Q_{water} experiences a nearly linear increase with the increased ambient temperature in both summer and winter time. It can be illustrated by the fact that higher ambient temperature makes contributes to higher water heat gain Q_{water}. When the ambient temperature is higher than the temperature of the outer curtain wall surface, the outdoor air is another heat source to the HPeAVCW system, increasing the water heat gain Q_{water}. When the ambient temperature is lower than the temperature of the outer curtain wall surface, a high ambient temperature means a low temperature difference between the outer curtain wall surface and the outdoor air. This leads to less heat loss, through convection and radiation, from the outer curtain wall surface to the outdoor environment and, as a result, the water heat gain Q_{water} increases.



(a)

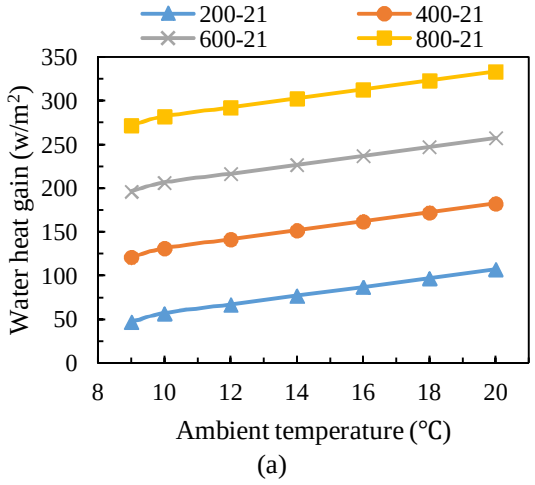


(b)

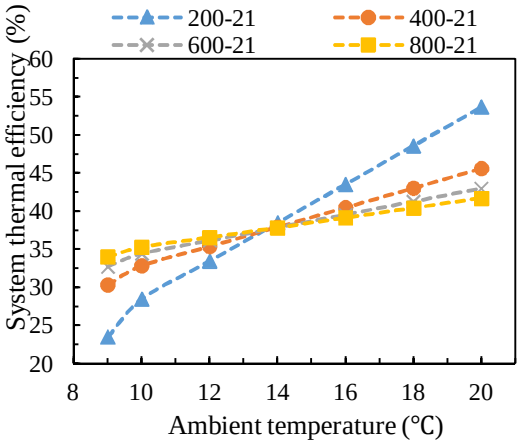
Fig. 3 Effects of outdoor weather condition on the HPeAVCW system performance in summer time ($\dot{V}$ = 240 L/h, T_{in} = 15℃)

On the other hand, The absorbed solar thermal energy by the outer surface of the curtain wall increases with the increased solar irradiation intensity I_o, directly increasing the water heat gain Q_{water}.

Fig. 3(b) and Fig. 4(b) show how system thermal efficiency η changes under different outdoor weather conditions. When solar irradiation intensity I_o keeps constant, system thermal efficiency η increases with the increased ambient temperature. In addition, increase rates of the system thermal efficiency are different under different solar irradiation intensities I_o. The increase rate of the system thermal efficiency η is low when solar radiation intensity I_o is high and vice versa. For example, increased rates are 52.02% and 13.22% respectively when solar irradiation intensities I_o are 200 W/m^2 and 800 W/m^2 in summer time. Increased rates are 30.18% and 7.71% respectively when solar irradiation intensities I_o are 200 W/m^2 and 800 W/m^2 in winter time.



(a)



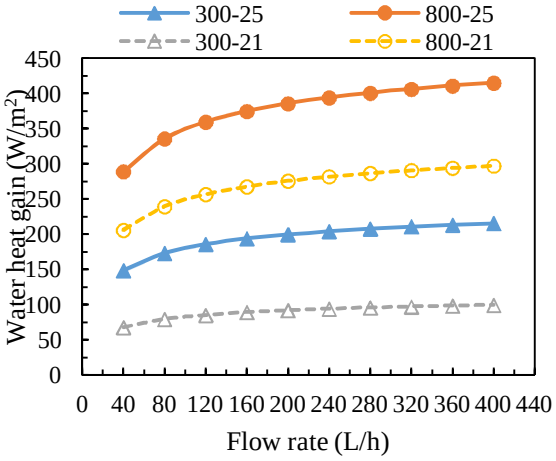
(b)

Fig. 4 Effects of outdoor weather condition on the HPeAVCW system performance in winter time ($\dot{V}$ = 240 L/h, T_{in} = 15℃)

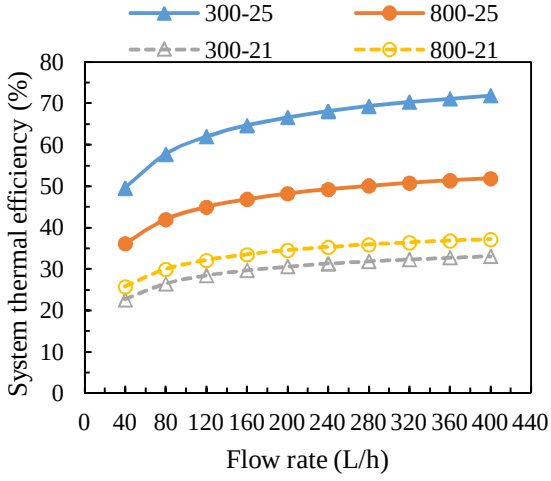
E. Effect of inlet flow rate $\dot{V}$ on system thermal performance

The velocity of flowing domestic water in the upper water box affects the heat transfer between the condenser section of heat pipe and the moving water. A lower flowing velocity could prolong heat exchange time but reduce heat transfer coefficient between the flowing water and the condenser section of heat pipe. Thus, it is necessary to study on the effect of inlet water flow rate $\dot{V}$ on system thermal performance.

The flow rate of inlet water $\dot{V}$ ranges from 40 L/h to 400 L/h, while the inlet temperature T_{in} keeps constant, at 15℃. The ambient temperatures respectively are 32℃ and 11℃ in the summer time and the winter time, and the indoor temperatures are 25℃ and 21℃ respectively. Fig.5 shows how water heat gain Q_{water} and system thermal efficiency η change with different inlet flow rates $\dot{V}$ under various weather data.



(a)



(b)

Fig. 5 Effects of inlet flow rate $\dot{V}$ on the HPeAVCW system performance (T_{in} = 15℃)

It can be seen that when solar irradiation intensity I_o and inlet water temperature T_{in} keep constant, the water heat gain Q_{water} and the system thermal efficiency η increase with the increased flow rate $\dot{V}$. This is due to that high flow rate $\dot{V}$ increases the Reynolds, which results in higher coefficients in the calculation formula of Nusselt. Thus, the convection heat transfer coefficient between the condenser section

of heat pipe and the flowing water increases. When flow rate $\dot{V}$ is less than 120 L/h, the increased flow rate has a clear effect on the system performance. When flow rate $\dot{V}$ is greater than 120 L/h, increasing flow rate $\dot{V}$ has a negligible influence on the system performance. With the increased flow rate $\dot{V}$ varies from 40 L/h to 120 L/h, increased rates of the water heat gain Q_{water} are 37.22 W/m^2, 70.34 W/m^2, 17.36 W/m^2, and 50.92 W/m^2 in cloudy summer time, sunny summer time, cloudy winter time and sunny winter time, respectively. Besides, increased rates of the system thermal efficiency η are 12.41%, 8.79%, 5.79%, and 6.36% in cloudy summer time, sunny summer time, cloudy winter time and sunny winter time, respectively. However, when the flow rate $\dot{V}$ increases from 120 L/h to 400 L/h, increased rates of the water heat gain Q_{water} are only 21.52 W/m^2, 40.17 W/m^2, 10.21 W/m^2, and 29.41 W/m^2 in cloudy summer time, sunny summer time, the winter time and sunny winter time, respectively. Meanwhile, increased rates of the system thermal efficiency η are only 7.17%, 5.02%, 3.41%, and 6.36% in cloudy summer time, sunny summer time, cloudy winter time and sunny winter time, respectively. Therefore, the optical value of the inlet flow rate $\dot{V}$ is 120L/h for the studied system.

When flow rate $\dot{V}$ rises from 40L/h to 400L/h, the water heat gain Q_{water} increases from 148.69 W/m^2 to 215.57 W/m^2, 289.13 W/m^2 to 414.89 W/m^2, 69.71 W/m^2 to 99.31 W/m^2, 205.83 W/m^2 to 297.29 W/m^2 in cloudy summer time, sunny summer time, cloudy winter time and sunny winter time, respectively. The system thermal efficiency η increases from 49.56% to 71.86%, 36.14% to 51.86%, 22.64% to 33.11%, 25.73% to 37.16% in cloudy summer time, sunny summer time, cloudy winter time and sunny winter time, respectively.

F. Effect of inlet water temperature T_{in} on system thermal performance

The wickless heat pipe is known as thermal diode, which means the heat can only be transferred from the lower evaporator section to the upper condenser section and cannot be transferred in the reverse direction. For this reason, heat pipe does not work when the temperature of flowing water in water box is higher than the temperature of heat pipe condenser section. The following numerical simulations were carried out when inlet temperatures are ± 2°C, ± 4°C higher than the ambient temperature, namely 28°C, 30°C, 34°C and 36°C in summer time and 7°C, 9°C, 13°C and 15°C in winter time.

Fig. 6 and 7 show how useful water heat gain Q_{water} and system thermal efficiency η of the HPeAVCW system change under different inlet water temperatures in summer and winter time. As can be seen from Fig. 6 and 7, both water heat gain Q_{water} and system thermal efficiency η reduce with the increase of inlet water temperature.

The inlet temperature has greater effect on the HPeAVCW system in claudy time than that in sunny time, because the lower absorbed solar energy in cloudy time makes the system more sensitive to temperature difference between the flowing water in upper water box and the condenser section of heat pipe. When the inlet water temperature increases from 28°C to 36°C in summer time, water heat gain Q_{water} and system thermal efficiency η are respectively reduced from 129.62 W/m^2 to 82.54 W/m^2, from 318.48 W/m^2 to 271.05 W/m^2, from 43.21% to 27.51% and from 39.81% to 33.88% in cloudy and sunny time. In winter time, when inlet water temperature increases from 7℃ to 15°C, water heat gain Q_{water} and system thermal efficiency η are respectively reduced by 44.75 W/m^2 and 45.02 W/m^2; 14.92% and 5.63% in cloudy and sunny time.

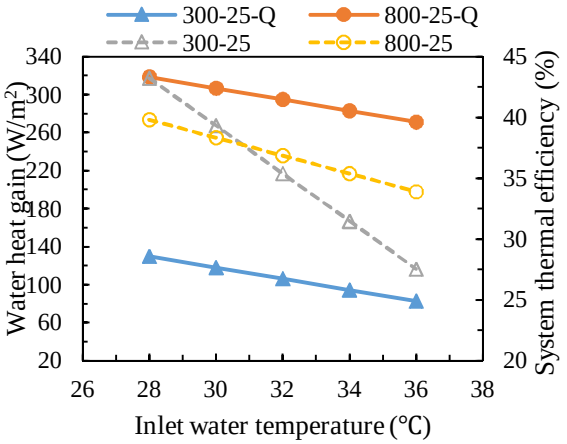


Fig. 6 Effects of inlet water temperature T_{in} on HPeAVCW system performance in summer time ($\dot{V}$ = 240L/h)

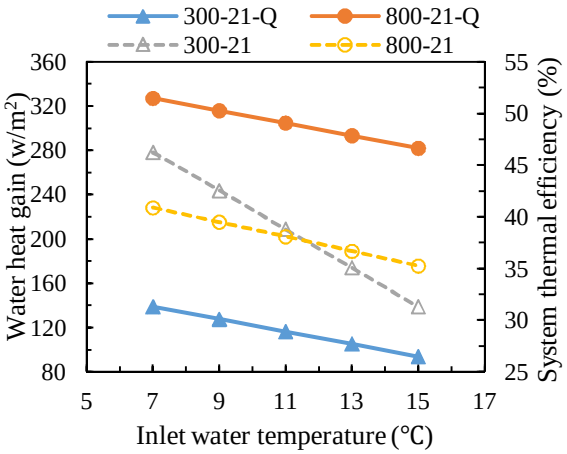


Fig. 7 Effects of inlet water temperature T_{in} on HPeAVCW system performance in winter time ($\dot{V}$ = 240L/h)

Therefore, lower inlet domestic water temperature is helpful to improve the thermal performance of the HPeAVCW system. It is necessary to insulate the domestic water supply pipe well and avoid the water

supply pipe in the direct sun without shading when the system works.

CONCLUSIONS

In this paper, a novel HPeAVCW system which can preheat domestic water is proposed and studied numerically. The mathematical model of the HPeAVCW system is developed and solved with the finite volume method. The system is simulated under steady state to observe effects of some operating parameters on the novel HPeAVCW system performance. The numerical results are listed below:

1. When solar irradiation intensity I_o keeps constant, water heat gain Q_{water} and system thermal efficiency η exhibit increased trends with the increased ambient temperature in both summer and winter time. Moreover, when the ambient temperature keeps constant, water heat gain Q_{water} and system thermal efficiency η increase with the increased solar irradiation intensity I_o. Therefore, the HPeAVCW system would have a better thermal performance when it is applied to the climate with high solar irradiation intensity and high ambient temperature.

2. Water heat gain Q_{water} and system thermal efficiency η rise with the increased inlet flow rate $\dot{V}$. However, enhancements of the water heat gain Q_{water} and the system thermal efficiency η are not obvious when the flow rate $\dot{V}$ increases from 120L/h to 400L/h. Thus, optical value of the inlet flow rate $\dot{V}$ is 120L/h for the studied system.

3. The HPeAVCW system has better thermal performance when inlet water temperature T_{in} of the upper water box is low. Therefore, it is necessary to insulate the domestic water supply pipe well and avoid direct exposure to the sunlight when the system works.

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