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Innovative Dual Storage Heat Tank Combination Solar Thermal, Air Conditioners and Heat Pump of Water Heating Systems

(Inovasi Tangki Penyimpanan Dual Haba Gabungan Haba Suria, Penyaman Udara dan Pam Haba melalui Sistem Pemanasan Air)

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ABSTRACT

Tropical or subtropical countries are very suitable for the development of solar and heat pump technology. This paper proposed the integration of air conditioners that exhaust heat with solar energy to enhance the overall efficiency of thermal energy conversion. The analysis of thermal storage tanks of different volumes showed that a two-ton air conditioner operating for an hour produced double energy than normal sunshine for a day. With thermal storage tanks of fixed volume, the integration of air conditioners of different tons with solar energy indicated that air conditioners of less tons produced faster and more efficient energy conversion. Therefore, this paper proposed that the modification of condenser in domestic air conditioner into water-cooled condenser not only enhance the energy efficiency of air conditioners but also increased hot water supplies since hot water from air conditioners could be integrated into solar water heaters. By doing so, energy conservation and carbon reduction could be achieved.

Keywords: Air conditioner; energy conversion; solar energy; thermal storage tanks

ABSTRAK

Negara-negara tropika atau subtropika sangat sesuai bagi pembangunan teknologi tenaga suria dan pam haba. Kertas ini mencadangkan perintegrasian penyaman udara yang menggunakan haba dan tenaga suria untuk meningkatkan kecekapan keseluruhan penukaran tenaga haba. Analisis tangki penyimpanan haba dengan isi padu yang berbeza menunjukkan bahawa penyaman udara dua tan yang beroperasi selama sejam menghasilkan tenaga dua kali ganda daripada cahaya matahari untuk satu hari. Dengan tangki penyimpanan haba dan isi padu yang tetap, integrasi penyaman udara daripada tan yang berbeza dengan tenaga suria menunjukkan bahawa penyaman udara dengan tan yang rendah cepat menghasilkan dan lebih cekap dalam penukaran tenaga. Oleh itu, kertas ini mencadangkan pengubahsuaian kondenser penyaman udara domestik ke kondenser pengairan sejuk bukan sahaja untuk meningkatkan kecekapan tenaga penyaman udara tetapi juga menambah bekalan air panas memandangkan air panas daripada penyaman udara boleh diintegrasikan ke dalam pemanas air suria. Dengan melakukan demikian, pemuliharaan tenaga dan pengurangan karbon boleh dicapai.

Kata kunci: Penyaman udara; penukaran tenaga; tangki penyimpanan haba; tenaga suria

INTRODUCTION

Hepbasli and Kalinci (2009) have studied a heat pump water heater (HPWH) operates on an air conditioners compressor driven vapor-compression cycle and pumps energy from the air in its surroundings to water in a storage tank, thus raising the temperature of the water. HPWHs are a promising technology in both residential and commercial applications due to both improved efficiency and air conditioning benefits. Kim et al. (2004) designed a dynamic model of a water heater system. From the simulation, the larger size caused additional heat loss during the hot water storage period. Therefore, the tank size should be optimized in a design process to minimize both the heat loss and the performance degradation. Baek et al. (2005) has studied the compression heat pump using wastewater as a heat source system, the yearly mean operating COP of the heat pump was 4.5-5.0 which has higher value than that of conventional heat pump system using ambient air heat source and the heat pump could provide over 90% of the instant hot water load and satisfy 100% of the hot water load, except for on weekends in winter. In Taiwan, Huang et al. (2003) develop an integral-type solar-assisted heat pump water heater (ISAHP-1), the average energy consumption is 0.019 kWh/L of hot water at 57°C that is much less than the backup electric energy consumption of the conventional solar water heater and the pure electric heater.

The solar water heating system, using clean and sustainable solar energy, is heating equipment free from pollution that not only reduces our dependence on oils or nuclear energy but also promotes environmental protection. By Taiwan Power Company, the installation of solar water heating systems in Taiwan is around 5%, covering an installation area of more than million square meters. It is inferred that the average daily insolation of a square meter for a year saves 68 L of oil equivalent and reduces 190 kg of CO_2 emission. Therefore, the enhancement of energy conservation and carbon reduction has become a global-scale objective.

Materials and Methods

RESEARCH METHOD

Solar water heating system was unable to supply hot water at night or in cloudy days. Supplementary heaters have a long heating cycle and power consuming. Even in winter, rainy or cloudy days, they still consume electricity. Besides, they are limited in places for installation and affected the beauty of cities. Energy saving and safety have become the ultimate goal when it comes to the development of new hot water supply systems. Solar energy and heat pump technology have been regarded as the most mature and reliable ways of saving energy.

Direct expansion solar-assisted heat pump (DX-SAHP) systems have been proposed as viable alternatives to conventional solar-assisted (SAHP) system (Chaturvedi et al. 1998; Hawlader et al. 2001; Omojaro et al. 2013). These studies demonstrated theoretically and experimentally that a DX-SAHP could work satisfactorily with a very high efficiency on sunny days. Ito et al. (1999) have experimental DX-SAHP system of a 350 W rated heating capacity in a previous study which can achieve a COP of 5.3 at noon on a sunny day in winter, when the condenser water inlet temperature was 40°C. Xu et al. (2006) presented a solar-air source heat pump water heater (SAS-HPWH) demonstrated that water heater which took the advantages of both utilizing solar energy and heat pump technology, not only was able to improve the overall energy efficiency for hot water heating, but also helped to solve the deficiency of not being able to work properly on rainy days. Hot water at 55°C may be readily produced at all weather conditions.

The integration of solar energy with heat pump technology has been mainly applied to large-scale heating systems, such as school dorms. So far small-scale domestic heating systems have not been popular. In southern Taiwan where the average temperature is above 26°C, solar water heaters could be installed on the top of townhouses. It is a pity that the heat energy exhausted to the outdoor via air-cooled condensers is wasted. The change of condenser in domestic air conditioner into water-cooled type enhances the energy efficiency and overall effectiveness of air conditioners. Once integrated into solar water heater or electric water heater, those water turns into domestic hot water and increases hot water supplies. The original energy-consuming electric heaters become energy-saving and the utility rate of gas-operated heaters also decreased, leading to energy conservation, carbon reduction and safety. Therefore, the study on the improved effectiveness of integrating wasted hot water from air conditioners with solar/electrical water heaters could be applied to and popularized in domestic heating systems.

Searching for the Best Solution

PRINCIPLES OF SOLAR WATER HEATERS

In 1980s, most of the studies on performance improvement tried to enhance each component in the collector, as optimal operating conditions and performance variables for various conditions, manifold designs, optical designs, solar collector tubes array and heat transport in solar collector tube (Kim et al. 2007; Morrison et al. 2004). In 1990s, the solar collector integration and performance evaluations were representative topics of that time (Grass et al. 2004; Shah et al. 2004). Solar water heaters absorb the radiant energy and convert it into heat energy to heat up water. According to Fourier's heat conduction law, heat flux (i.e. the rate of flow of radiant energy across a given area) is proportional to the magnitude of a temperature gradient. When the heat energy is transmitted to the inner wall of a pipe, heat convection then transmits the energy to the liquid in the pipe, thus heating up the water (Cengel & Boles 2002; Incropera et al. 2007) (Figure 1).

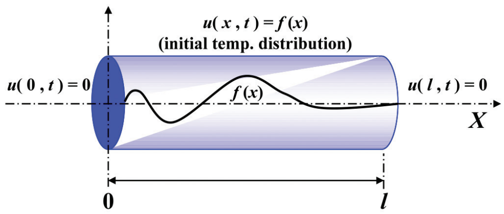

FIGURE 1. The optimal thermal conduction of a stick with an even boundary condition

The equation serving as the model of thermal conduction of a stick is as follows:

$$u_t = k\, u_{xx}, \tag{1}$$

where $u = u(t, x)$ is the bifunction of t and x. x is the space variable, so $x \in [0,L]$, where L is the length of the stick. t is the time variable, so $t \geq 0$. Given the following initial condition:

$$u(0, x) = f(x) \quad \forall x \in [0, L], \tag{2}$$

where f is given a constant function. With the following initial condition:

$$u(t, 0) = 0 = u(t, L) \quad \forall t > 0. \tag{3}$$

To have a solution not identically equal to zero to satisfy the boundary condition (3) and have the following form:

$$u(t, x) = X(x)T(t), \tag{4}$$

This technique is called the method of separation of variables. Substitute u into (1),

$$\frac{T'(t)}{kT(t)} = \frac{X''(x)}{X(x)}.$$

Because the right side of the equation only depends on x, while the left side depends on t, both sides are equal to some constant $-\lambda$. Hence,

$$T'(t) = -\lambda kT(t). \tag{5}$$

$$X''(x) = -\lambda X(x). \tag{6}$$

The fact that there is no solution to $\lambda \le 0$ is evidenced (6): Given $\lambda < 0$, then the real numbers B and C allow:

$$X(x) = Be^{\sqrt{-\lambda x}} + Ce^{-\sqrt{-\lambda x}}.$$

From (3) we get:

$$X(0) = 0 = X(L).$$

Therefore $B = 0 = C$, implying that u is identically equal to zero. Given $\lambda = 0$, then the real numbers B and C allow:

$$X(x) = Bx + C.$$

Based on the aforementioned calculation of (3), it is inferred that u is identically equal to zero. Therefore $\lambda > 0$ becomes a necessary condition, the real numbers A, B and C allow:

$$T(t) = Ae^{-\lambda kt}$$

$$X(x) = B \sin\left(\sqrt{\lambda}x\right) + C \cos\left(\sqrt{\lambda}x\right).$$

From (3), we know $C = 0$. Therefore the positive integer n allows:

$$\left(\sqrt{\lambda}x\right) = n\frac{\pi}{L}.$$

Hereby we get the solution to the heat as (4).

Generally speaking, the solutions that meet (1) and (3) still meet (1) and (3) given that they are added together. In fact, the solutions that meet (1), (2) and (3) could be obtained from the following equation:

$$u(t,x) = \sum_{n=1}^{+\infty} D_n \left(\sin\frac{n\pi x}{L}\right) e^{-\frac{n^2\pi^2 k t}{L^2}},$$

where

$$D_n = \frac{2}{L}\int_0^L f(x)\sin\frac{n\pi x}{L}dx.$$

OPERATING PRINCIPLES OF HEAT PUMPS

First law of thermodynamics is the extension of the law of conservation of energy to a non-isolated system, in which work (W) and heat (Q) can be transferred into or out of the system:

$$\Delta E_{\text{int}} = Q + W.$$

ΔE_{int} is the variable of state of the system. W remains positive if there is work done on the system and vice versa:

$$dE_{\text{int}} = \delta Q + \delta W.$$

The compressed Freon in air conditioners exhausts the absorbed heat to the outdoor. According to the law of conservation of energy, the energy exhausted to high temperature area (Q_H) is equivalent to the work (W_e) done to the air conditioners and the energy (Q_L) absorbed indoors. What air conditioners carry is heat, so air conditioners are formally termed as heat pump-to circulate heat with the use of a compressor (Figure 2).

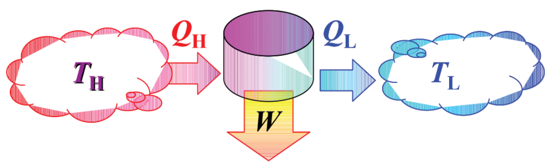

FIGURE 2. First law of thermodynamics

OPERATING PRINCIPLES OF WATER-COOLED AND AIR-COOLED DOMESTIC AIR CONDITIONERS

The technology of using a heat pump for space conditioning and domestic hot water heating in residences has been developed for half a century. Ji et al. (2003) have showed that the laboratory test results on the prototype have been very much promising; the performance under the space-cooling mode can be jacked up by 38% through simultaneous water-heating. Hosoz et al. (2004) compared the three types of condensers, namely the air-cooled, water-cooled and evaporative condensers. It was found that the water-cooled condenser has a higher refrigeration capacity of 2.9~14.4%, and a higher COP of 1.5~10.2%. In Taiwan, scholar Hu and Huang (2005) utilizes cellulose pad as the filling material of the cooling tower of water-cooled domestic air-conditioner system (WDACS), the system COP can exceed 3.45 while the wet-bulb temperature is under 27°C.

WDACS uses fan radiator system and modified flat-plate heat exchanger equivalent to its operating efficiency. A flat-plate heat exchanger has two inlets. One is for the feron and the other is for the cooling water. The high-temperature feron produced from the operation of condenser is connected to the feron pipeline in the flat-plate heat exchanger, with the upper inlet and the lower outlet forming a circulation system. The cooling water from a cold water tank flows into the other pipeline in the flat-plate heat exchanger. Contrary to the feron connection, the cooling water refluxes to the tank with the connection of lower inlet to upper outlet. When the high-temperature feron flows into the flat-plate heat exchanger, the cold water in the heat exchanger is used for heat dissipation and cooling, enabling the air conditioner to keep producing cool air (Figure 3).

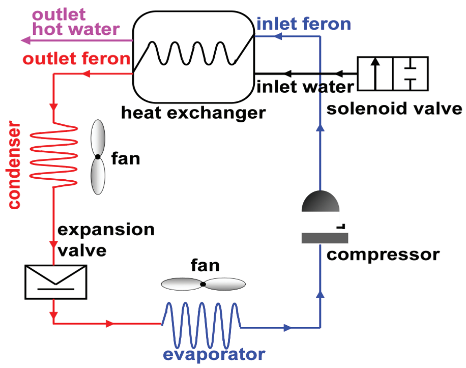

FIGURE 3. The operating principle of water and air-cooled type domestic air conditioner

STRUCTURE OF FLAT-PLATE HEAT EXCHANGER

A flat-plate heat exchanger is composed of punched wavy stainless steel plates, with two adjacent plates arranged at an opposite angle of 180°. The ridges of the two plates form crisscross contacts. After vacuum welding, those contacts form the crisscross channel system capable of enduring high pressure. This system makes the fluids in the flat-plate heat exchanger to form violent turbulence, thus reaching high thermal conduction (Kim & Kim 2005; Mon et al. 2004). If the fluids are delicate and close enough to form a continuum that does not contain ionization, velocity is relatively slow compared with velocity of light. The momentum equation of the Newtonian solutions is the Navier-Stokes equation, a nonlinear differential equation stating that there is a linear interdependence among stress, velocity and pressure. The Navier-Stokes equation does not have a closed-form equation. Unless it is simplified, it could only be used for computational fluid dynamics.

In addition to mass, momentum and the law of conservation of energy, the equation of state in thermodynamics makes pressure the function of other variables. One example is the ideal gas law:

$$p = \frac{\rho R_u T}{M},$$

where p is the pressure; ρ is the density; R_u is the gas constant; M is the molecular mass; and T is the temperature. The current study aimed to develop an efficiency enhancement system that integrated the wasted heat from air conditioners with solar water heaters. In the current study, domestic window-type or multi-split-type air conditioners were modified into water-cooled type. The temperature of condenser and evaporator was, respectively, set at 50°C and 10°C to control the air temperature at 16°C. Flat-plate heat exchanger was used as the condenser, whose volume could be greatly decreased to fit the interior of the air conditioner. Therefore, the exterior and volume of the air conditioner remained unchanged. An additional water tank was parallel connected to the bottom of the original tank of the solar system. Supplementary cold water located at the bottom of the additional water tank was automatically infused into the system only with the running of hot water.

RESULTS AND DISCUSSION

ANALYSIS AND RESULTS OF THE SOLUTION

The innovative design of the dual storage tank (i.e. the inner tank and the outer tank) decreased the mixture of cold water and hot water. At the bottom of the inner tank and the outer tank was a communication port. Hot water of lower temperature at the bottom of the outer tank infused into the inner tank because water in the inner tank infused into the outer tank. The inner tank had two outlets, respectively, for air-conditioned circulating cold water and solar cold water. While the inner tank supplied air-conditioned circulating cold water and solar cold water, air-conditioned circulating hot water and solar hot water infused into the center of the outer tank. The use of hot water outlet was in a relatively higher place in the outer tank. The air conditioner and the water pump operated simultaneously, while the fan of the condenser did not operate. The cold water in the inner tank was heated by the heat exchanger and infused into the outer tank. After a period of time (e.g. 20 min), the fan of the condenser started to operate when the temperature difference between the cold water inlet and the hot water outlet in exchanger was below 4°C, with the aimed to improve the condensation deficiency. When the air conditioner stopped, so did the water pumps.

During daytime when solar heat worked, the produced hot water infused into the outer tank via natural convection (if needed, an additional water pump could be used to enhance circulation). When the cold water in the inner tank infused into the outer tank, a certain amount of water in the outer tank infused into the inner tank. The continuous circulation of cold water and hot water gradually increased the water temperature of the outer tank. While the infused hot water temperature from air conditioner would not be higher than the feron temperature of the condenser, the temperature of solar circulating hot water was free from this limitation. When the use hot water flowed out, supplementary cold water from high-pressure tap water tower or high-position tower infused into the inner tank. A layer of thermal insulation material was added to the exterior of the outer tank to lower the effect of climate on water temperature (Figure 4).

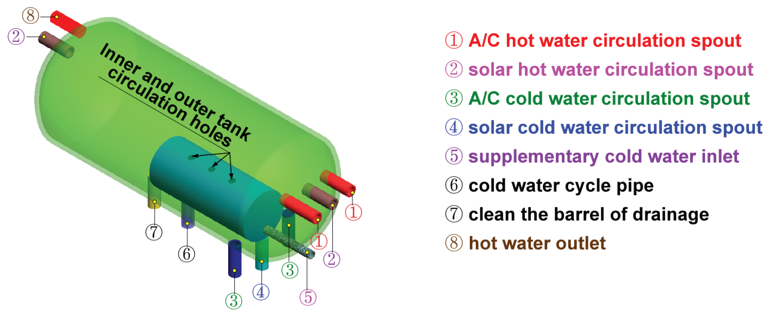

FIGURE 4. The innovate design of the dual storage heat tank

The Parallel Connection of Solar Water Heater and Window-Type Air-Cooled Air Conditioner

The single-pipe hot water circulation spouts as well as cold water circulation spout was modified into multiple-pipe type. The combination of water heater and water-/wind-cooled air conditioner meant to connect the cold water circulation tube in the hot water tank with the flat-plate heat exchanger cold water inlet in an air conditioner. Cold water was heated because of the absorption of feron energy via a heat exchanger and was later stored in hot water tank via circulation. The combination could be customized, such as the combination of one solar water heater with one air conditioner or multiple air conditioners to enhance the heat exchange efficiency, with which the quantity and temperature of hot water storage increased and the time for using hot water prolonged. Whenever an air conditioner operated, it generated hot water as well. The integrated system (Figure 5) contributed greatly to household energy-saving effectiveness. Figure 6 is the study dual storage heat tank combination solar thermal, water-cooled air conditioner and flat-plate heat exchanger systems.

Experimental Details

Test of the Solar Water Heater

The first step was the installation of two solar water heaters, including the standard 300 L two solar collector panels and the oversize 450 L two solar collector panels. In order to understand the heating power of the two water heaters, they were tested in the same condition: regular sunshine, normal weather (28 to 30°C) and from 8 am to 5 pm. The local convective heat flux was:

$$q' = h(T_s - T_\infty),$$

where q' is the local heat flux (dq / dA); h is the local convection coefficient; T_s is the surface temperature; and T_∞ is the ambient temperature.

Through a surface, the overall thermal conduction was calculated and the integration q was:

$$q = \int_{A_s} q' \, dA_s,$$

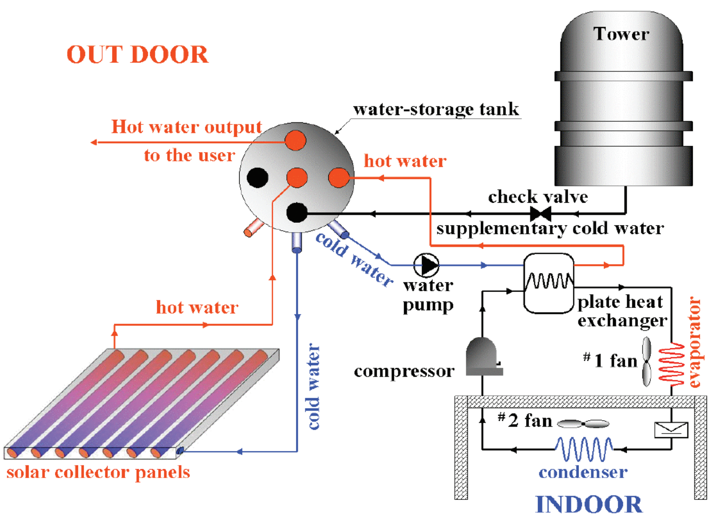

FIGURE 5. Dual storage heat tank combination solar thermal, air conditioners of heating systems

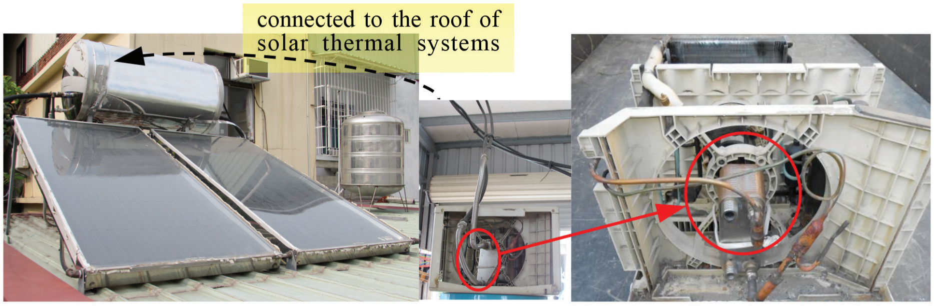

FIGURE 6. The actual system architecture diagram of this study

where A_s is the surface area; and q is the overall thermal conductivity (energy/unit of time).

Hence, the average convection coefficient $\bar{h}$ was:

$$q = \bar{h}A_s\,(T_s - T_\infty).$$

The analysis of energy accumulation of 300 and 450 L tanks via the aforementioned equation of the flow of radiant energy [$Q = m \times C_p \times (T_2 - T_1)$] showed that the accumulated energy of standard two solar collector panels in both tanks were around 11100 Kcal/h. The equation of energy supply from solar water heater was:

$$\frac{(\text{daily energy supply})}{(\text{insolation on tilted surface})} \times (\text{area of solar collection}) \times (\text{solar collection efficiency})$$

$$= \frac{4Kwh}{m^2 - day} \times 2m^2 \times 2\,panels \times \frac{0.5 \times 3600\left(\frac{\sec}{h}\right)}{4.186Kcal}$$

$$= 6{,}880\frac{Kcal}{day}.$$

TEST OF THE PARALLEL CONNECTION OF AIR CONDITIONER AND SOLAR WATER HEATER

In the current study, changes of water temperature were analyzed in the three conditions: one-ton air conditioner only, two-ton air conditioner only and the combination of the two types of air conditioners. The results in Table 1 indicated that in different conditions (i.e. one air conditioner or multiple conditioners), a 1 h operation led to significant increase in water temperature, evidencing that the integration of the wasted heat from air conditioners with solar water heaters significantly enhanced the water temperature. The fact that high-temperature air resulted from wasted heat was cooled not only reduced the greenhouse effect but also increased the amount of usable hot water. This eco-friendly concept has been the focus of the current study.

CONCLUSION

The results of the experiment suggested that the wasted heat from air conditioners was able to reach high efficiency of thermal energy conversion more than other heating systems.

TABLE 1. The effectiveness of the integration of 450-liter solar water heater with air conditioner

Dual storage heat tank and water-cooled air conditioner	Time	08:00	10:00	12:00	14:00	16:00	17:00
450 L solar water heaters	temp.(°C)	28	32	39	47	52	53
(3,4,5 months)	Kcal	0	1,800	4,950	8,550	10,800	11,250
450 L solar water heaters	temp.(°C)	28	34	42	54	64	66
(6,7,8 months)	Kcal	0	2,700	6,300	11,700	16,200	17,100
450 L solar water heaters	temp.(°C)	28	33	40	49	57	60
(9,10,11 months)	Kcal	0	2,250	5,400	9,450	13,050	14,400
450 L solar water heaters	temp.(°C)	28	31	36	44	50	52
(12,1,2 months)	Kcal	0	1,350	3,600	7,200	9,900	10,800
1T air conditioner	temp.(°C)	28	33	45	54	59	60
start-up time 11:00~12:00	Kcal	0	2,250	7,650	11,700	13,950	14,400
2T air conditioner	temp.(°C)	28	32	51	60	66	67
start-up time 11:00~12:00	Kcal	0	1,800	10,350	14,400	17,100	17,500
Two air conditioners	temp.(°C)	28	33	56	65	70	72
start-up time 11:00~12:00	Kcal	0	2,250	12,600	16,650	18,900	19,800

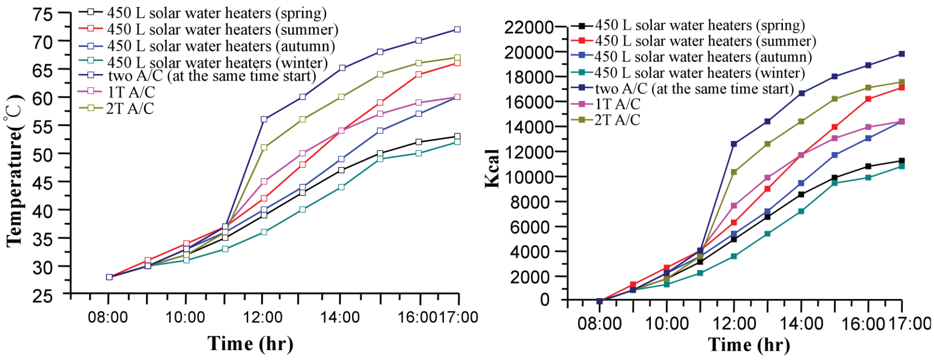

FIGURE 7. The comparison of water inlet and outlet temperatures

In addition, the solar water heating system is not limited to only one air conditioner, capable of the simultaneous operation of multiple air conditioners. The more the air conditioners or the longer the operation time, the higher the temperature of the water and the better the heating efficiency (Figure 6).

The heating curve in Figure 7 has demonstrated a stable heating trend in solar water heaters. The results indicated that air conditioners produce more energy than solar water heaters (i.e. a two-ton air conditioner operating for 1 h produced the same amount of energy as normal sunshine for a day). Therefore, the integration of wasted heat from air conditioners with solar water heaters not only enhanced heating efficiency but also leads to energy conservation and carbon reduction.

The current study aimed to develop a brand-new product. The integration of air conditioners with solar water heaters helps alleviate global warming because this integration is highly efficient in energy conservation and carbon reduction. Based on sustainability, coexistence and ecological equilibrium, products that consume energy should be modified and improved to enter the world of energy conservation, energy creation and multi-function industries.

REFERENCES

Baek, N.C., Shin, U.C. & Yoon, J.H. 2005. A study on the design and analysis of a heat pump heating system using wastewater as a heat source. *Solar Energy* 78: 427-440.

Çengel, Y.A. & Boles, M.A. 2002. *Thermodynamics an Engineering Approach*. 4 ed. Boston: McGraw Companies, Inc.

Chaturvedi, S.K., Chen, D.T. & Kheireddine, A. 1998. Thermal performance of a variable capacity direct expansion solar assisted heat pump. *Energy Conversion and Management* 39: 181-191.

Grass, C., Schoelkopf, W., Staudacher, L. & Hacker, Z. 2004. Comparison of the optics of non-tracking and novel types of tracking solar thermal collectors for process heat applications up to 300°C. *Solar Energy* 76: 207-215.

Hawlader, M.N.A., Chou, S.K. & Ullah, M.Z. 2001. The performance of a solar assisted heat pump water heating System. *Applied Thermal Engineering* 21: 1049-1065.

Hepbasli, A. & Kalinci, Y. 2009 A review of heat pump water heating systems. *Renewable and Sustainable Energy Reviews* 13: 1211-1229.

Hosozl, M. & Kilicarslan, A. 2004. Performance evaluations of refrigeration systems with air-cooled, water-cooled and evaporative condensers. *International Journal of Energy Research* 28: 683-696.

Hu, S.S. & Huang, B.J. 2005. Study of a high efficiency residential split water-cooled air conditioner. *Applied Thermal Engineering* 25: 1599-1613.

Huang, B.J. & Lee, C.P. 2003. Long-term performance of solar-assisted heat pump water heater. *Renewable Energy* 29: 633-639.

Huang, B.J. & Chyng, J.P. 1999. Integral-type solar-assisted heat pump water heater. *Renewable Energy* 16: 731-734.

Incropera, F.P., DeWitt, D.P., Bergman, T.L. & Lavine, A.S. 2007. *Fundamentals of Heat and Mass Transfer*. 6th ed. New Jersey: John Wiley & Sons, Inc.

Ito, S., Miura, N. & Wang, K. 1999. Performance of a heat pump using direct expansion solar collectors. *Solar Energy* 65: 189-196.

Ji, J., Chow, T., Pei, G., Dong, J. & He, W. 2003. Domestic air-conditioner and integrated water heater for subtropical climate. *Applied Thermal Engineering* 23: 581-592.

Kim, Y. & Seo, T. 2007. Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube. *Renewable Energy* 32: 772-795.

Kim, Y. & Kim, Y.C. 2005. Heat transfer characteristics of flat plate finned-tube heat exchangers with large fin pitch. *International Journal of Refrigeration* 28: 851-858.

Kim, M., Kim, M.S. & Chung, J.D. 2004. Transient thermal behavior of a water heater system driven by a heat pump. *International Journal of Refrigeration* 27: 415-421.

Li, C.A. & Jhang, K.C. 2011. China's solar hot water system issued fair use case analysis. *Taiwan Power Company 100 annual savings album*.

Mon, M.S. & Gross, U. 2004. Numerical study of fin-spacing effects in annular-finned tube heat exchangers. *International Journal of Heat and Mass Transfer* 47:1953-1964.

Morrison, G.L., Budihardjo, I. & Behnia, M. 2004. Water-in-glass evacuated tube solar water heaters. *Solar Energy* 76: 135-140.

Omojaro, P. & Breitkopf, C. 2013. Direct expansion solar assisted heat pumps: A review of applications and recent research. *Renewable and Sustainable Energy Reviews* 22: 33-45.

Shah, L.J. & Furbo, S. 2004. Vertical evacuated tubular-collectors utilizing solar radiation from all directions. *Applied Energy* 78: 371-395.

Xu, G., Zhang, X. & Deng, S. 2006. A simulation study on the operating performance of a solar-air source heat pump water heater. *Applied Thermal Engineering* 26: 1257-1265.

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