Performance of Photovoltaic Solar Assisted Heat Pump System in Typical Climate Zone

P. Gang, J. Jie, H. Wei, L. Keliang and H. Hanfeng
Department of Thermal Science and Energy Engineering
University of Science and Technology of China, Hefei City, Anhui, China
Email: jijie@ustc.edu.cnT
(Received on 26 Feb 2006, revised on 4 Apr 2007)

Abstract

A novel application of photovoltaic solar assisted heat pump (PV-SAHP) system is reported in this paper. Performance tests were conducted in an experimental rig with condensing water temperature. The temperature varies from 15 to 55 ^{O}C. The performance in terms of photovoltaic/photothermic conversions and refrigeration cycle are analyzed in typical climate zone in China. The results show that the COP of heat pump, the $COP_{p/t}$ of system and the photovoltaic efficiency of PV system are 6.3, 9.0 and 13.2% respectively. These indicated significant improvement of the performance of heat pump and the PV system.

Nomenclature

A	area of solar cell, m^2
c	specific heat, J/kg.
COP	coefficient of performance
$COP_{p/t}$	comprehensive coefficient of thermal-and-electrical performance
I	solar radiation, W/m^2
m	mass flow rate, kg/s
Q_c	condenser capacity, W
T	temperature, ^{O}C
W_{com}	compressor power, W
W_p	output power of PV cell, W
η_p	photovoltaic efficiency
η_{power}	electricity generation efficiency

Introduction

Recent development in the integration of heat pump and solar technology lies in the use of direct-expansion solar collectors to replace the standard air-source evaporator in a heat pump system. This heat pump system using solar radiation as the evaporating heat source is known as the solar assisted heat pump (SAHP) system. The advantage of this system is the higher evaporating temperature of refrigerant at the evaporator-collector owing to the solar heating effect. This increases the coefficient of performance (COP) of the heat pump. From the solar technology point of view, the refrigerant as the working fluid at the solar collector undergoes phase change at a relatively low temperature. The heat loss of collector decreases evidently and the energy utility efficiency is therefore improved.

SAHP system was firstly proposed by P. Spornon [1]. Recent years, SAHP has received much attention since the energy problem, environmental pollution and greenhouse effect aggravated badly. S. K. Chaturvedi [2] studied SAHP system for a long period and he pointed out that evaporating temperature of SAHP was about 0 to 10 ^{O}C higher than ambient temperature and which performance was better than conventional heat pump. V. Badescu [3] carried out the numerical simulation investigation about SAHP system based on his own meteorological model. Two kinds of integrated SAHP system for nearly commercial application were developed by G. L. Morrison [4] and B. J. Huang [5], and tested chronically in Australia and Taiwan respectively. These existed researches were mainly on the thermal performance of solar energy and heat pump.

On the other hand, the conversion of solar energy to electricity by photovoltaic cells has attracted public attention and photovoltaic modules are expected to be installed on the roofs of many houses and building in the near future. However, the electrical conversion efficiency of a photovoltaic module is presently 15 percent at most and the majority of the solar radiation on the photovoltaic module is converted to heat which increases PV cell operating temperature and decreases photovoltaic efficiency. Hybrid photovoltaic/thermal (PV/T) system is designed to simultaneously generate electrical and thermal energy by using water as heat removal fluid under PV module. Many theoretical and experimental studies have been performed on the PV/T system since J. E. C. Kern [6] gave the main concept of PV/T system in 1970.

Bergene and Lovvik [7] presented a calculated model based on an analysis of energy transfers and predicted the total efficiency about 60 to 80%. B. J. Huang [8] designed a PV/T collector, with a commercial PV module on a flat-box polycarbonate heat-collecting plate, and introduced the concept of primary-energy saving efficiency to evaluate the performance of PV/T systems. Although a water-based PV/T system was able to achieve a higher overall energy output per unit aperture area when compared to side-by-side PV and solar water-heating system, the photovoltaic efficiency of the hybrid system unavoidably drops considerably in the afternoon hours within a day exposure. This is because the temperature rise of the removal fluid (water) must be finally up to a level that meets the water heating demand. If the evaporating refrigerant of SAHP is used as the cooling medium of the PV cells, the lower operating temperature of PV cell and higher photovoltaic efficiency will be easily achieved. At the same time, the heat absorbed from solar radiation in the PV-evaporator will be output at a higher temperature in the condenser for use by heat pump recycle. This novel application of photovoltaic/thermal technology with heat pump is known as photovoltaic solar assisted heat pump (PV-SAHP) system.

A PV-SAHP prototype was constructed with the PV cells laminated onto the flat evaporator plate in this study. So a portion of the solar energy received in PV evaporator was converted to electricity and the rest was converted as heat source of heat pump. The heat energy was then absorbed by the refrigerant and carried over to the condenser. Photovoltaic efficiency was increased in this way due to the lowered PV cell operating temperature as a result of the refrigerant evaporation process. The COP of heat pump was also substantially improved because of the solar energy absorption. Presented below are the working principle, the testing method and the dynamic photovoltaic/thermal performance of PV-SAHP system.

Experimental Facility

Heat pump system

Fig.1 shows an indicative diagram of our PV-SAHP test rig. The basic components are the PV evaporator, air-source evaporator, variable-frequency compressor, air-cooled condenser, water-cooled condenser, and electricity-operated expansion valve. Other accessories not shown in the diagram for simplicity include refrigerant filter, liquid trap, four-way valve, anti-vibration mount, auxiliary capillary tubing, and the like. A brief description of the system operation is given below.

The Air-source evaporator and PV evaporator are arranged for parallel operation, though normally only the PV evaporator is in service. The air-source evaporator will add in at the time with insufficient solar radiation and otherwise the evaporating temperature will fall much below the ambient temperature. Air-cooled condenser and water-cooled condenser are also installed in parallel. When the water-cooled condenser is in service, the circulating water can supply domestic hot water and space heating indirectly. If by the air-cooled condenser, space heating can be supply directly. In principal, this PV-SAHP system is designed for multi-functional to provide space cooling, space heating and domestic water-heating, through the changes of the shut-off valves and four-way valve positions.

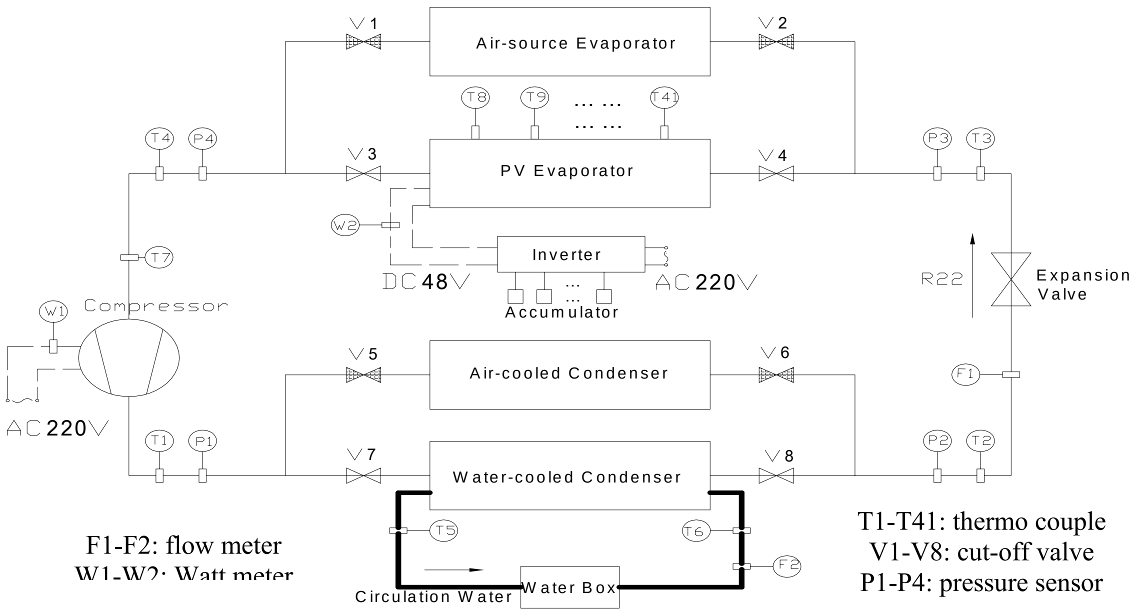

Fig. 1 Schematic diagram of the PV-SAHP experimental setup

Panasonic 2C*123*7AA02 variable-frequency compressor is used in our experimental system, which frequency ranged from 15 Hz to 120 Hz, corresponding to the range of input power from 150 W to 1300 W. The electricity-operated expansion valve can automatically adjust its position in matching the operation frequency of the compressor.

In the PV evaporator, the R22 absorbs heat energy and enters the compressor as a superheated vapor. With its pressure and temperature lifted up by the compressor input power, the refrigerant gas enters the condenser where it condenses, and leaves as a sub-cooled liquid. Sensible and latent heats are released in the process and passed on to the circulating water and/or air streams. The throttling of the refrigerant in the expansion valve converts it to a low temperature wet-vapor before entering the PV evaporator and repeats another heat pump cycle. Because of the direct solar energy absorption, the evaporating temperature and pressure in the PV evaporator are higher than in the conventional heat pump. This leads to a higher system coefficient of performance. In cold winter, this is also good for protecting the evaporator from frosting.

Photovoltaic system

The photovoltaic system mainly consists of PV cells, inverter, controller, accumulator, electric appliance box, and load. The PV cells and the evaporating plate are laminated together to form a PV evaporator module. Fig. 2 shows its outside view and Fig. 3 is a cross-section view (part plan). The whole PV evaporator is composed of nine PV evaporator modules. The total aperture area is 5.49 m^2 and the total PV cell area is 4.59 m^2. The 1.5 mm thick base panel of the PV evaporator is made of aluminum alloy. The PV cells are packed between two transparent TPT (tedlar-polyester-tedlar) layers, with an intermediate layer of

Fig. 2 Photograph of PV-SAHP system

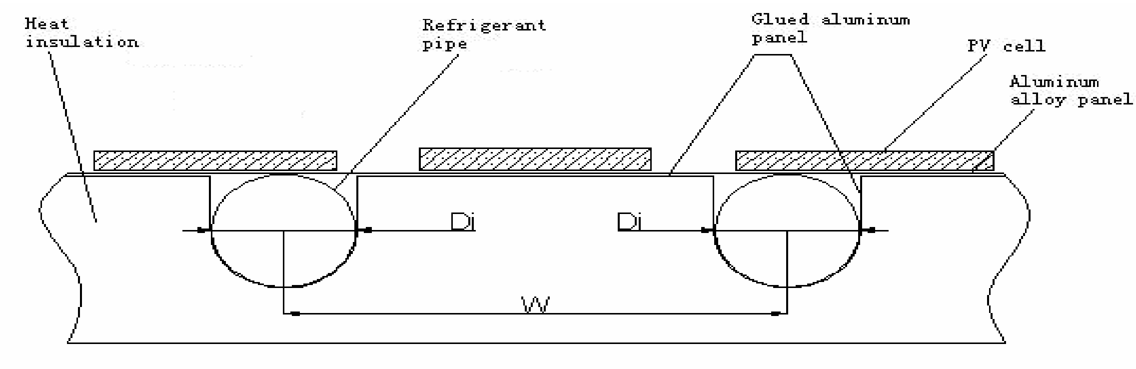

Fig. 3 Cross sectional view of PV evaporator

EVA (ethylene-vinyl acetate) in between. The whole lot of PV cells, TPT and base panel are processed in a vacuum laminating machine to provide high-quality bonding for achieving the required electrical insulation and thermal conduction. Through a bending machine, 6mm diameter (D_i) refrigerant cover tubing was bent to the form of snake lines, winding with a spacing of 130mm (W) between adjacent sections. The adhesion process of the two aluminum panels (0.5mm omega plate plus 1.5mm flat plate), with the winding refrigerant tube sealed between them, is under precise pressure control to ensure good quality thermal conductance. The whole PV evaporator plate is fitted inside an aluminum frame.

The PV cells are of single-crystalline silicon type. The photovoltaic characteristics are: 0.63V open circuit voltage, 5.12 A short-circuit current, 2.40 W maximum power, 0.53 V and 4.58 A at maximum power point, and 15.4% electrical efficiency. The above specification is for the sample testing conditions of 1000 W/m^2 solar irradiation, 25 ^oC ambient temperature, and 156.25 cm^2 cell area. The 48 V Direct Current generates at the PV module is converted to 220 V Alternating Current at 50Hz. The electricity is then either consumed by the system load or transferred to the national grid. A list of the experimental testing and monitoring devices in use are given in Table 1.

Table 1 List of testing and monitoring devices

Device	Specification	Quantity	Parameters tested
Pressure Sensor	0-30atm (Huba506, Sweden)	4	Pressure of evaporator and condenser
Power Sensor	WBP112S91 and WBI022S (WeiBo, China)	2	Compressor input power (AC) and PV module output power (DC)
Refrigerant Mass Flow meter	R025S116N (MicroMotion, USA)	1	Refrigerant mass flow
Pyranometer	TQB-2 (Sunlight, China)	1	Solar radiation on PV evaporator surface
Thermocouple	0.2mm copper-constantan (USTC, China)	41	Temperature of PV evaporator, condensing water, compressor exit, ambient air.
Anemometer	EC21A (Wei Tian, China)	1	Wind velocity
Data logger	34970A, (Agilent, USA)	1	Test data acquisition

Experiments and Analysis

System parameters and experiments

If Q_c is the condenser capacity and W_{com} the compressor power, the COP of heat pump is given by

$$COP = \frac{Q_c}{W_{com}} . \tag{1}$$

For the water-cooled condenser under test,

$$Q_c = mc(T_{wout} - T_{win}) \tag{2}$$

where, m is the mass flow rate of the circulating water, c is the specific heat of water, T_{win} and T_{wout} are the water temperatures at the condenser inlet and outlet respectively.

The photovoltaic (cell) efficiency of the PV evaporator is given by

$$\eta_p = \frac{W_p}{I \cdot A} \tag{3}$$

where, W_p is the output power of the solar cells, I the incoming solar irradiance, and A the area of solar cells.

As a PV-SAHP system generates not only heat energy but also electrical energy, a comprehensive coefficient of thermal and electrical performance ($COP_{p/t}$) is defined here, in that the output power of the PV cells is transformed into the equivalent thermal power through the use of the average electricity-generation efficiency (η_{power}) of a coal-fired power plant, i.e.

$$COP_{p/t} = \frac{Q_c + W_p / \eta_{power}}{W_{com}} \tag{4}$$

A commonly used value of η_{power} is 38%. During the test, refrigerant was flowing in the direction as indicated in Fig. 1, with valves 1, 2, 5, 6 being closed and valves 3, 4, 7, 8 being opened. The compressor was running at a constant frequency of 40 Hz, and the power supply was from the national grid. The DC output power of the PV cells was transformed into AC by the inverter, and deposited in accumulators. The mass flow rate of the circulating water was measured 0.217 kg/s.

The experiment was processed at the University of Science and Technology of China (USTC) in the city of Hefei, which is located at Central China, at latitude 31°53’ N and longitude 117°15’ E. For optimizing the winter operation, the south-facing PV evaporator was set at a tilt angle of 38^{o}. Instant solar irradiance and ambient temperature are shown in Fig. 4.

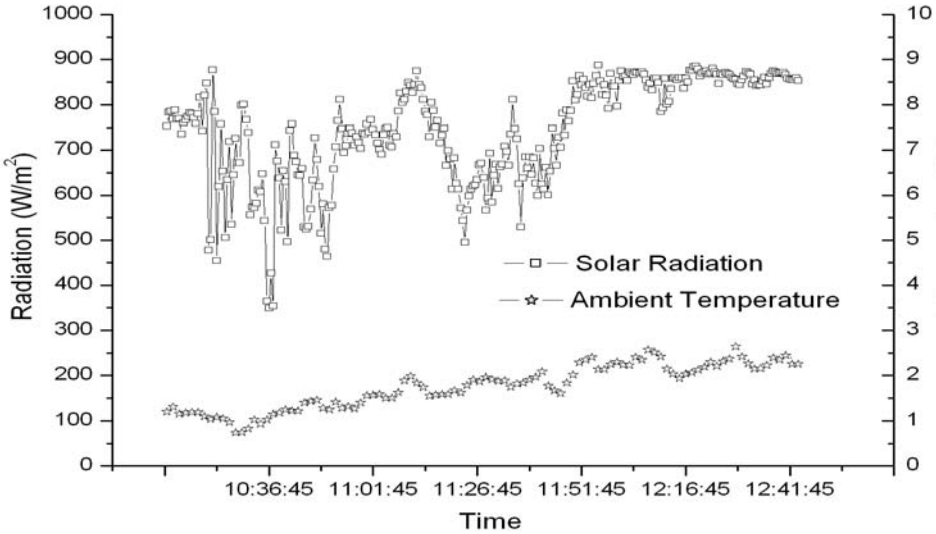

Fig. 4 Instantaneous weather data in experimental period

Results and Discussion

Fig. 5 shows the variations of water temperature, COP and $COP_{p/t}$ along with testing time. During the test period, the condensing heat was rejected to condensing water, and the water temperature rose from 15 ^{O}C to 55 ^{O}C. The COP of the PV-SAHP system reached its peak value of 9.5 at the initial stage of test. And then COP declined with the temperature increasing of condensing water. When water temperature reached 55 ^{O}C, the COP declined to 4.1. The average COP of heat pump was 6.3 through the test. Evidently the PV-SAHP system had a better performance than an ordinary air-source heat pump.

Fig. 6 shows the condensing capacity and compressor power varied along with the testing time. The compressor power rose gradually from 234 W to 677 W along with the condensing temperature rising. On the other hand, the condensing capacity didn’t decline linearly along with the testing time, because the solar radiation had a contrary effect on the heat pump with the condensing temperature rising.

In Fig. 7 the photovoltaic efficiency kept above 12.6% with the variation of PV power output throughout the test process. The average photovoltaic efficiency was 13.2%. Comparing to ordinary photovoltaic modules, the PV performance of PV-SAHP had a better improvement and less fluctuation. The evaporation of refrigerant kept the PV cell working at a lower temperature even when the solar irradiance was strong at noon. This assured the PV cells higher conversion efficiency than normal PV module. To allow a comprehensive evaluation of the system performance, $COP_{p/t}$ is introduced in this paper as in equation (4). During the testing, the $COP_{p/t}$ reached its maximum at 14.8, and the average at 9.0.

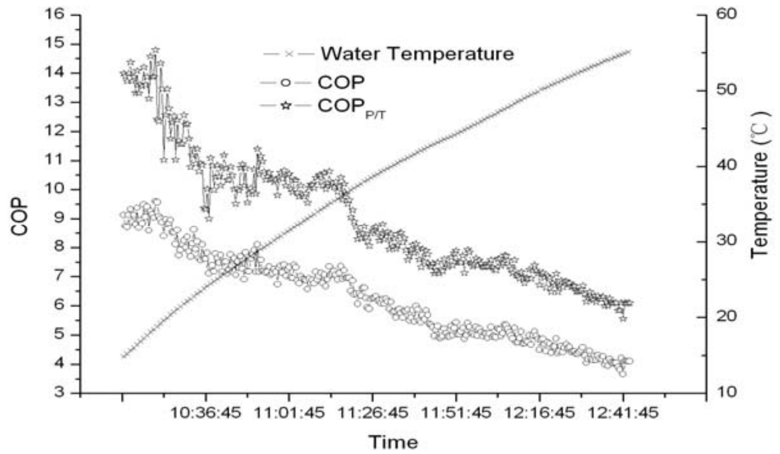

Fig. 5 Variation of COP, $COP_{p/t}$ and water temperature

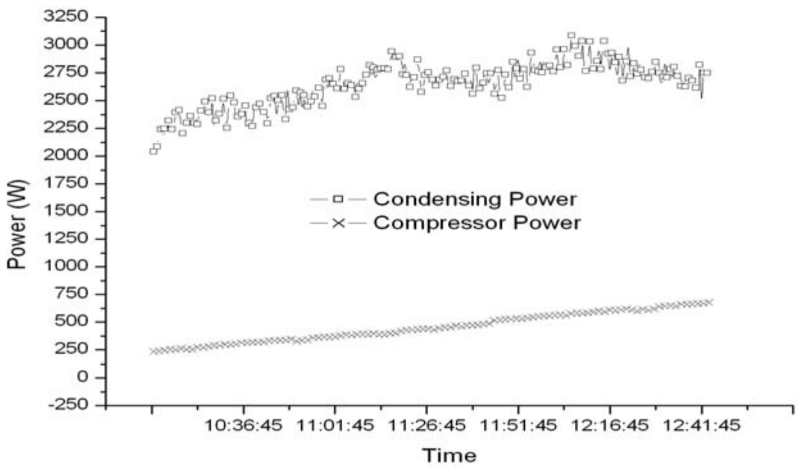

Fig. 6 Variation of condensing capacity and compressor consumption power

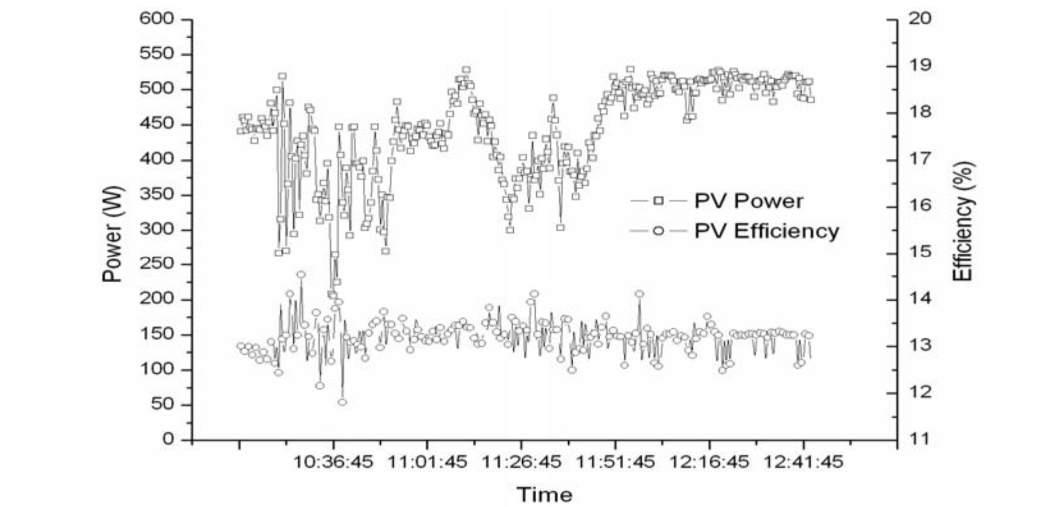

Fig. 7 Variation of PV electricity output and PV efficiency

Fig. 8 shows the PV power was larger than the compressor power before 11:20 AM. And then with the increase of the water temperature, the compressor power also increased gradually and got higher than the PV power. The PV output performance was mainly related with solar radiation, and the compressor power was closely correlated with condensing temperature. The average value of the compressor power tested in this experiment was 452 W and the average PV power was 443 W.

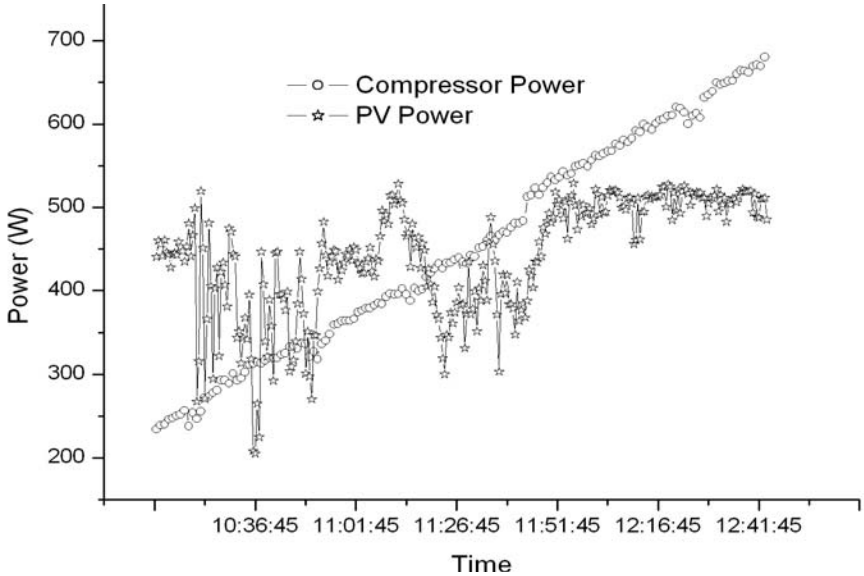

Fig. 8 Contrast of PV electricity output and compressor consumption power

Fig. 9 shows the condensing pressure, the evaporating pressure and the compression ratio changed along with the testing time. During the testing process, the average compression ratio was 2.4, which was evidently lower than the air-source heat pump water heater.

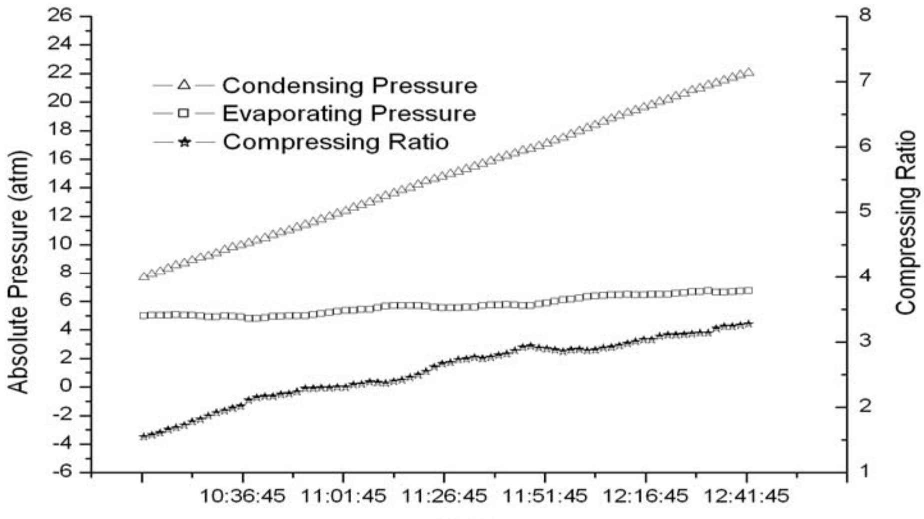

Fig. 9 Variation of condensing pressure, evaporating pressure and compressing ratio

Conclusion

Following conclusion may be drawn from this study.

- Coefficient of performance (COP) and comprehensive coefficient of thermal and electrical performance ($COP_{p/t}$) obtained from this study were 6.3 and 9.0 respectively.

- Photovoltaic efficiency of PV system was 13.2%.

- The PV-SAHP system may be used for significant improvement of performance of heat pump and PV system.

Acknowledgement

Work in this paper was sponsored by National Natural Science Foundation of China (No. 50478023) and Anhui Province Natural Science Foundation of China.

References

[1] P. Sporn. and E. R. Ambrose, "The heat pump and solar energy", in Proc., World Symposium on Applied Solar Energy, Phoenix, Arizona, pp. 159-170, 1955.

[2] S. K. Chaturvedi, Y. F. Chiang and J. Y. Shen, "Thermal performance of a direct expansion solar-assisted heat pump", Journal of Solar Energy, Vol. 33, pp. 155-162, 1984.

[3] V. Badescu, "First and second law analysis of a solar assisted heat pump based heating system", Journal of Energy Conversion and Management, Vol. 43, pp. 2539-2552, 2002.

[4] G. L. Morrison, "Simulation of packaged solar heat-pump water heaters", Journal of. Solar Energy, Vol. 53, pp. 249-257, 1994.

[5] B. J. Huang and J. P. Chyng, "Performance characteristic of integral type solar-assisted heat pump", Journal of Solar Energy, Vol. 71, pp. 403-414, 2001.

[6] J. E. C. Kern, "Combined photovoltaic and thermal hybrid collector system", in Proc., IEEE Photovoltaic Specialists, Washington DC.USA, pp. 1153-1157, 1978.

[7] T. Bergene and O. M. Lovvik, "Model calculations on a flat-plate solar heat collector with integrated solar cells", Journal of Solar Energy, Vol. 55, pp. 453-462, 1995.

[8] B. J. Huang, T. H. Lin and W. C. Huang, "Performance evaluation of solar photovoltaic/thermal systems", Journal of Solar Energy, Vol. 70, pp. 443-448, 2001.