View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Environmental Sciences 11 (2011) 790 – 797

Procedia Environmental Sciences

# Numerical Simulation of the Performance of a Solar-Assisted Heat Pump Heating System

Weibo Yang[1], Jielian Zhu[1], Mingheng Shi[2], Zhenqian Chen[2]

*[1]School of Energy and Power Engineering Yangzhou University Yangzhou, China*
*[2]School of Energy and Environment Southeast University Nanjing, China*
*yangwb2004@163.com*

---

***Abstract***

Solar-assisted heat pump heating system (SAHPHS), which combines solar heating and heat pump technology into a combined system and can improve both the solar utilization efficiency and COP of heat pump, is a promising energy utilization technology. In order to discuss the influences of area of solar collector and heat capacity of storage water tank on the operation performance of SAHPHS, a system simulation model was developed based on the unit model. The numerical simulation on the performance of the SAHPHS was performed by the model, and an optimization function was also presented to optimize it. The results obtained and the optimization algorithm presented in this study can provide a preference for the optimization design of SAHPHS.

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and/or peer-review under responsibility of the Intelligent Information Technology Application Research Association.

*Keywords:*Component; Solar-assisted heat pump; Heating performance; Numerical simulation

---

## 1. Introduction

Solar energy systems and heat pumps are two promising means of reducing the consumption of fossil resources, and hopefully, the cost of residential heating. An intelligent extension is to try to combine the two into a combined system named as solar-assisted heat pump (SAHP)[1]. It is widely believed that the SAHP can improve both the utilization efficiency of solar energy and the COP of heat pump and thus is a promising energy saving device for energy utilization.

During the last decade, a number of work has been performed by some researchers in the design, modeling and experiments of SAHP. These studies mainly may be categorized into four groups as follows[2]: (1) SAHPS for water heating, (2) SAHPS with storage for space heating, (3) SAHPS with direct expansion for space heating, and (4) solar-assisted ground source heat pump system. For each system, the size of solar collector and storage volume are two important design parameters for optimize its operation performance.

1878-0296 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and/or peer-review under responsibility of the Intelligent Information Technology Application Research Association.
doi:10.1016/j.proenv.2011.12.121

In this paper, a system simulation model was developed to investigate the influences of size of solar collector and storage volume on system perfromance, and a optimization algorithm was also presented to optimize it.

## 2. Development of the system simulation model of solar-assisted heat pump heating system

As shown in Fig.1 that the system investigated here consists of four fundamental components namely: solar collector, energy storage water tank, heat pump and room thermodynamic system.

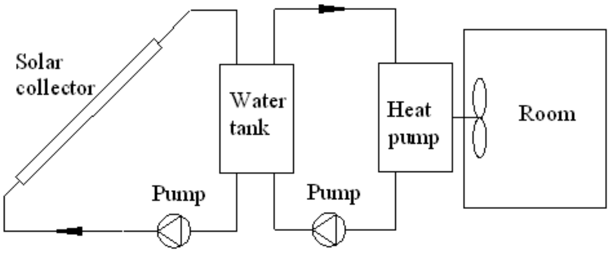

Figure.1 Schematic of solar-assisted heat pump heating system

### 2.1Solar Collector

A typical flat-plate solar collector is used in this study, The rate of useful energy gain was calculated by the Hottel-Whiller steady-state equation[3].

$$Q_u = I_c A_c F_R \left[(\tau\alpha)_e - U_l (t_{ci} - t_a) / I_c\right] \tag{1}$$

Energy balance for the collector can also be expressed as

$$Q_u = c_l m_l (t_{co} - t_{ci}) \tag{2}$$

From Eq.(1) and (2), we can obtain

$$t_{co} = \left(1 - \frac{A_c F_R U_l}{c_l m_l}\right) t_{ci} + \frac{A_c I_c F_R (\tau\alpha)_e}{c_l m_l} + \frac{F_R U_l A_c}{c_l m_l} t_a \tag{3}$$

where $Q_u$ is the useful energy gain of collector, W. $I_c$ is the incident solar radiation ,W/㎡. $F_R$ is the heat remove factor. $(\tau\alpha)_e$ is the effective transmissivity-absorptivity product. $U_l$ is the overall heat losses coefficient, W/㎡ K. $t_{ci}, t_{co}$ are inlet and outlet fluid temperature of collector, ℃. $T_a$ is outside ambient air temperature, ℃. $c_l$ is the mass specific heat of fluid, J/(kg.℃). $m_l$ is the mass flow rate of circulation fluid, kg/s.

### 2.2 Energy Storage Water Tank

In the energy storage water tank, the energy is stored mainly as sensible heat and a fully mixed water tank was assumed, thus the outlet water temperature from the storage tank is equal to the average water temperature in tank. Based on the energy balance, the energy equation for the water tank can be expressed as follows:

$$C_s M_s \frac{dt_s}{d\tau} + U_s A_s (t_s - t_a) + Q_e = Q_u \tag{4}$$

For a small time $\Delta\tau$ , the Eq.(4) can rewritten as

$$t_s(\tau + \Delta\tau) = t_s(\tau) + \left[Q_u - Q_e - U_s A_s (t_s - t_a)\right]\Delta\tau/(C_s M_s) \tag{5}$$

where $C_s M_s$ is the thermal capacity of storage medium of water tank, kJ/K. $t_s(\tau)$ the average water temperature of water tank，℃； $U_s$ is the heat losses coefficients of water tank，W/(㎡·℃)； $A_s$ is the heat losses area of water tank，㎡； $Q_e$ is the heat extraction amount of heat pump， W.

## 2.3Heat Pump

In this work, a water-air heat pump is selected, its performance depends on some main operating parameters, including fluid flow rate, inlet air and fluid temperature. For a given inlet air temperature and fluid flow rate, the performance depends only on the inlet fluid temperature. To compute the heat rejection in cooling mode, heat absorption in heating mode and the heat power consumption, the quadratic fitted equations by the manufacture's catalog data are used. For heating mode, the equations are as follows:

$$\frac{Q_{extraction}}{q_{heating}} = a_1 + a_2 t_{in} + a_3 t_{in}{}^2 \tag{6}$$

$$\frac{N}{q_{heating}} = b_1 + b_2 t_{in} + b_3 t_{in}{}^2 \tag{7}$$

where $a_1, a_2, a_3, b_1, b_2$ and $b_3$ are curve-fit coefficients of performance of heat pump determined by manufacture's catalog data. $q_{heating}$ is the instantaneous heat load, and can be calculated as

$$q_{heating} = q_n \times (t_z - t_n)/(t_w - t_n) \tag{8}$$

where $q_n$ is the design heat load for room. $t_n$ and $t_w$ are indoor and outdoor design temperature, respectively. $t_z$ is the outdoor air overall temperature considering solar radiation.

## 2.4Meteorological Model

In the present model, the ambient air temperature $t_a$ is modeled as[4]:

$$t_a(\tau) = \overline{t_a} + \Delta t_a \sin\left[\frac{\pi(\tau - 8)}{12}\right] \tag{9}$$

The instantaneous solar radiation incident $I_c(\tau)$ is assumed to vary sinusoidally with time τ between sunrise and sunset as[4]

$$I_c(\tau) = I_{c,\max} \sin\left[\frac{\pi(\tau - \tau_{rise})}{t_d}\right] \tag{10}$$

where $I_{c,\max}$ is the maximum value of $I_c(\tau)$ which corresponds to solar noon. $\tau_{rise}$ is the sunrise time and $t_d$ is the day length.

### *2.5Control Conditions*

- Solar collector control

The solar collector is control by on-off method for maximizing the utilization of solar energy during the day. Here a control strategy suggested by [4] is used.

On: when $t_{stag} - t_{ci} \geq 6$ ℃ and $t_{co} - t_{ci} \geq 2$ ℃

Off: when $t_{co} - t_{ci} < 2$ ℃ and $t_s > t_{s\max}$

where $t_{stag}$ is the average flat board temperature when fluid is stagnation, and can be calculated as

$$t_{stag} = t_a + (\tau\alpha)_e I_c / U_l \tag{11}$$

where $t_a$ is outside ambient air temperature, ℃. $(\tau\alpha)_e$ is the effective transmissivity-absorptivity product.

- Electric heater control

Here, an assistant electric heater should be added to prevent the inlet fluid temperature of heat pump from dropping to the minimum set value required for heat pump. According to the manufacturer, the set value is -4 ℃.

## 3. Numerical simulation of the performance of the solar-assisted heat pump heating system

Based on the model developed above, the numerical simulation on the operation performance of solar-assisted heat pump system was carried out. The calculated conditions were presented in Table I and the simulation results were shown in Figs.2~9, among which Figs.2-5 show the influences of collector area and Figs.6-9 indicate the influences of the thermal capacity of water tank.

Table 1 calculated conditions for the simulation

| **Variable** | $\overline{t}_a$ /℃ | $\Delta\overline{t}_a$ /℃ | $t_{s\max}$ /℃ | $t_{s\min}$ /℃ | $t_d$ |
|---|---|---|---|---|---|
| Value | 4 | 10 | 30 | -4 | 10 |
| **Variable** | $F_R$ | $(\tau\alpha)_e$ | $U_l$ | Us | $\tau$ |
| Value | 0.8 | 0.8 | 2.36 | 0.28 | 7:00 |
| **Variable** | $a_1$ | $a_2$ | $a_3$ | $b_1$ | $b_2$ |
| Value | 0.7113 | 0.0044 | -0.0001 | 0.2887 | -0.0044 |
| **Variable** | $c_l$/kJ/kgK | $m_l$/kg/s | $b_3$ | $t_a$ /℃ | $t_n$ /℃ |
| Value | 3.8 | 0.5 | 0.0001 | 0 | 6 |

### *3.1 Influences of the Collector Area on System Performance*

From Figs.2-3 we can find that the collector efficiency of solar collector gradually drop and the COP of heat pump will increase with the increase of collector area. This is caused mostly by the increase of heat loss of collector resulted from the increase of plate temperature. As is shown in Fig.4 that the average water temperature of water tank will increase with the increase of collector area, this inevitably increase the plate temperature. From Fig.5 we can further find that the total useful energy gain of collector and assisted electric power will increase and drop respectively with the increase of collector area, but the input power of heat pump seems to be invariable. So the collector area should not be design to be too bigger and could be optimized for obtain a good overall effect.

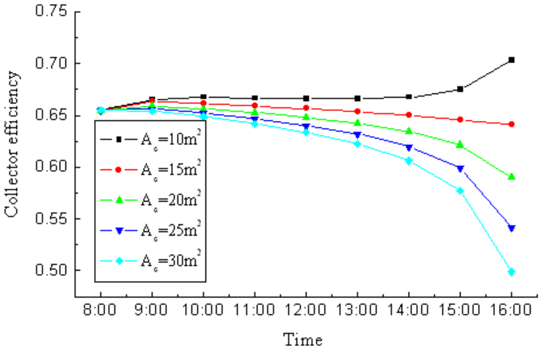

Figure.2 The variation of collector efficiency with time for different collector area

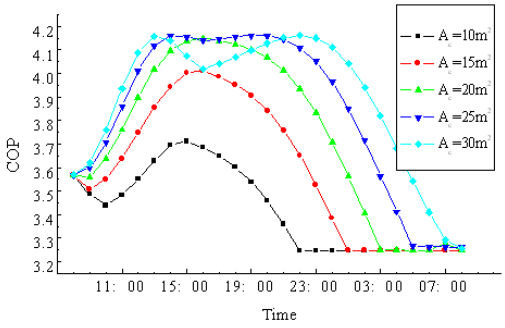

Figure.3 The variation of COP of heat pump with time for different collector area

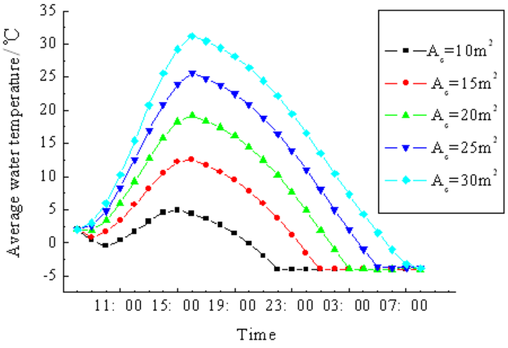

Figure. 4 The variation of average water temperature of water tank with time for different collector area

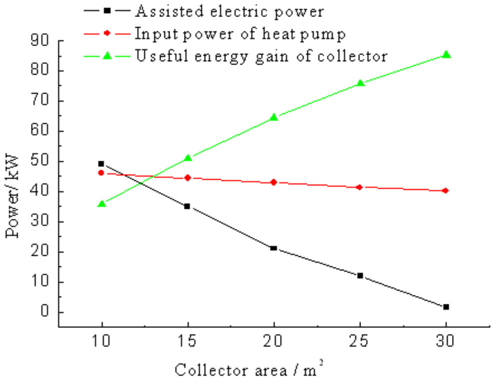

Figure.5 The variation of various power with the collector area

### 3.2 Influences of the Thermal Capacity of Water Tank on System Performance

Fig.6 shows that the collector efficiency will increase with the increase of thermal capacity of water tank and the increase degree gradually become small. From Fig.7 we can find that the increase of thermal capacity will result in the drop of COP, the most reason is that the average water temperature in water tank can drop when the heat capacity increase, this can be shown in Fig.8. Further analysis on Fig.9 can find that except assisted electric power, the input power and useful energy gain of solar collector seems to be invariable when the thermal capacity of water tank increase. Therefore, the thermal capacity of water tank, the same as solar collector, should not also be too large, and could be optimized by system simulation.

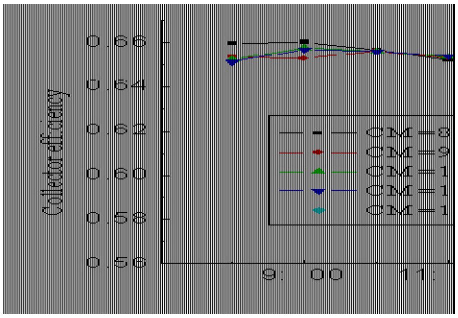

Figure.6 The variation of collector efficiency with time for different thermal capacity of water tank

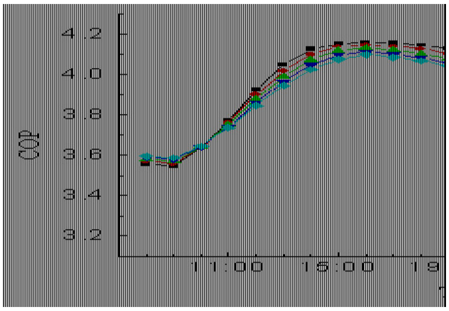

Figure.7 The variation of COP with time for different thermal capacity of water tank

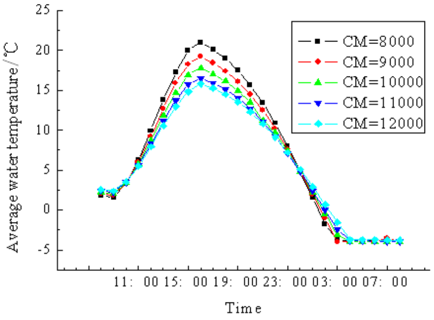

Figure.8 The variation of average water temperature of water tank with time for different thermal capacity of water tank

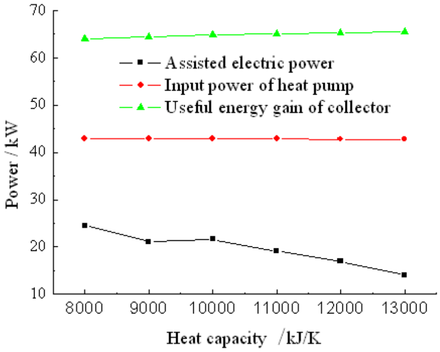

Figure.9 The variation of various power with thermal capacity of water tank

### *3.3Optimization method for the System*

In order to optimize the size of solar collector and volume of water in the system, the total power consumption and initial cost could be selected as two optimization objective functions, and the solar collector

area and the volume of water tank could be used as two optimization variables. According the system model developed above, the total power consumption and initial cost can be expressed as respectively

$$Fun1 = \sum_{i=1}^{n} W_i = f(A_c, V_s) \tag{12}$$

$$Fun2 = A_c P_1 + V_s P_2 \tag{13}$$

where $Fun1$ and $Fun2$ are the optimization objective functions used to calculate total power consumption and initial cost, respectively. $W_i$ is the instantaneous power consumption at *i* time. $P_1$ is the price of collector, and $P_2$ is the price of water tank. Above is a two-objective optimization problem and can be changed into a single-objective optimization by introducing a weigh factor, $\alpha$ . This can be expressed as

$$Fun = \alpha Fun1 + (1-\alpha)Fun2 \tag{14}$$

Where $\alpha$ a weigh is factor, and expresses that which is important among the variables.

Based on optimization function presented above, the system optimum calculation can be performed by several optimization algorithms such as Genetic Algorithm and Direct Search Algorithm.

## 4. Conclusions

A system simulation model on SAHPHS was developed based on the unit model. Based on the model, the numerical simulation on the operation performance of SAHPHS were performed to discuss the influences of collector area and heat capacity of water tank, the results shows that the area of solar collector and the thermal capacity of water storage tank should not be designed to be too large, and can be optimized based on the algorithm presented in this study.

## Acknowledgment

The work is supported by the Science and Technology Support Project of Jiangsu Province (BE2010699), the China Postdoctoral Science Foundation (20090461050), the Project of Research and Development from the Ministry of Housing and Urban-Rural Development of China (2008-K1-26), the Science and Technology Innovation Breed Fundation from Yangzhou University (2010CXJ030) and the New Century Talent Project of Yangzhou University-Excellent Youth Backbone Teacher (2008).

## References

[1]K. Kaygusuz, Investigation of a combined solar-heat pump system for residential heating. Part2: simulation results, Int.J.Energy Res, 1999, 23:1225-1237

[2]O.Ozgener, A.Hepbasli, A review on the energy and exergy analysis of solar assisted heat pump system, Renewable and Sustainable Energy Reviews, 2004,

[3]J.A. Duffie, W. A. Deckman, Solar Engineering of Thermal Process. New York: John Wiley and Sons,1980

[4]R Howell John, B Richard, C Gary. Solar-thermal energy systems: analysis and design. New York: McGraw-Hill Book Company, 1982.