Performance analysis of the solar-thermal assisted air-conditioning system installed in an office building

Masaya Okumiya[1,*], Takuya Shinoda[1], Makiko Ukai[1], Hideki Tanaka[2], Mika Yoshinaga[3], Kazuyuki Kato[4], Toshiharu Shimizu[4]

[1] *Nagoya University,Nagoya,Japan*
[2] *Chubu University,Kasugai,Japan*
[3] *Meijyo University,Nagoya,Japan*
[4] *Tohogas Co. Ltd.,Nagoya,Japan*

** Corresponding author. Tel: +81 527894653, Fax: +81 527893773,*
E-mail:okumiya@davinci.nuac.nagoya-u.ac.jp

Abstract: In this study, performance of the solar-thermal assisted air-conditioning system installed in an office building is investigated. In this paper, firstly the results of field measurements in winter (heating) and summer (cooling) are presented. Efficiency and performance of equipments which constitutes a system are investigated. Also the utilization efficiency of solar energy and the solar fraction are estimated for winter/summer season. In addition to analysis of field measurement data, system simulation of performance was conducted in this paper. Simulation program using in this study was developed as the tool for Life Cycle Energy Management of HVAC system. In this paper mathematical model of each equipment are presented as well as how to model total system . Although there are some limitations of solar system simulation with 1 hour time step, the calculation result was well in agreement in an actual measurement.

Keywords: *Solar-thermal assisted air-conditioning system, Field measurement, Simulation*

Nomenclature

Ac area of collector..... m2
C fluid thermal capacity rate ratio ……..-
Cmax higher capacity rate of heat exchanger in two side..... kW /C
Cmin lower thermal capacity rate of flow medium in two side ..... kW /C
C1 thermal capacity rate of fluid at primary side..... kW /C
C2 thermal capacity rate of fluid at secondary side..... kW /C
FE water flow rate through collector..... kg/h
G gas consumption of absorption machine in cooling ..... kW
J solar radiation kW/m2
N number of transfer units .....-
Qc collected heat ..... kW
Qhex actual heat exchange rate ..... kW
Qhexmax ideal maximum heat exchange ratekW
q load ratio of absorption machine in cooling .....-
Ta outdoor air temperature.....C
Tc,out collector outlet water temperature C
Tc,in collector inlet water temperature C
T1,in inlet water temperature of heat exchanger in primary side.....C
T1,out outlet water temperature of heat exchanger in primary side.....C
T2,in inlet water temperature of heat exchanger in secondary side C
T2,out outlet water temperature of heat exchanger in secondary side C
U heat loss coefficient of collctor.....$kW/m^2 \cdot s^{-1}$
UA overall heat transfer coefficient .....kW /C
Wmax higher flow rate of heat exchanger in two side.....kW /C
Wmin lower flow rate of heat exchanger in two side.....kW /C

α absorption rate of collector..... -
ε heat exchanger effectiveness ..... -
η thermal efficiency of collector..... -
τ transmittance of collector cover glass.....-
ω specific dissipation of turbulent kinetic energy.....s^{-1}

1. Introduction

Practical use of renewable energy is necessary for CO2 emissions reduction, especially, possibility of energy conversion by using solar thermal is high, and it is considered to be one of the effective means.

Although the solar-thermal-conversion air conditioning system combined with the absorption refrigerating machine was proposed at 1970's in Japan[1)2)], remarkable spread after that was not seen because of solar heat collection at high temperature having been difficult. Also there was not high performance thermal driven chiller (absorption machine) for effective use solar thermal energy.

In this paper, the actual proof examination of the air conditioning system which combined the solar collector and the gas absorption chiller/heater which can use solar heat is presented. The actual proof examination started from Jan. 2010 in Tsu City, Mie for the purpose to demonstrate effectiveness of solar HVAC system. Firstly the outline of building and system was described. Then performance of system in winter and summer season is presented and discussed. Furthermore the system simulation for solar system was intoroduced and possibility to represent the behavior of system is discussed.

2. Outline of Object Building and System

A building is 2,400m2 of total area and 4 stories. The appearance is shown in Fig. 1. The layout of equipments on roof is shown in Fig. 2, and specification of equipments is shown in Table 1. The appearance of two type of collector is shown in Fig.3. The system flow of diagram and outline of control are shown in Fig. 4.

3. Result of Actual Proof Examination

3.1 Thermal efficiency of collector

Fig. 5 shows the change of amount of heat collection Qc and thermal efficiency calculated by following equation.

$$Qc = (Tc,out - Tc,in) * FE \quad (1)$$

$$\eta = Qc / (J * Ac) \quad (2)$$

Fig.1 Appearance of building

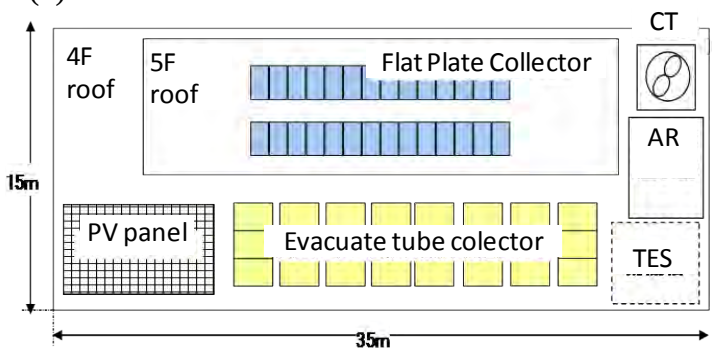


Fig.2 Layout of equipments on roof

Fig.3 Appearance of collectors

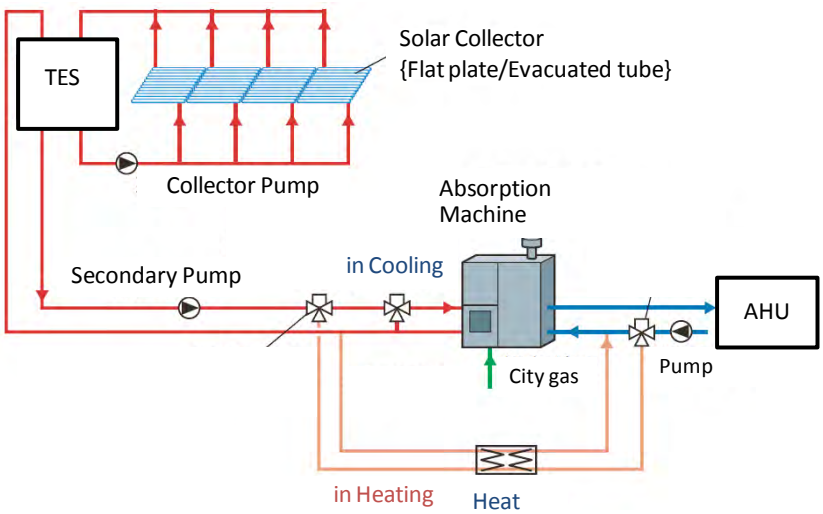


Fig. 4 System diagram of solar heating/cooling system

Table 1 Specification of equipments

Solar	Total are 139m^2	Flat plate
Collector	Medium : Water	2.0m^2 x 28
	Tilted angle : 25°	Evacuated tube
	Angle of direcstion : SSW30°	4.1m^2 x 20
Absorption	Three stage	
Machine	Cooling 527kW Heating 290kW	
TES	4.9m^3	

Fig. 6 shows daily solar irradiance and amount of heat collected in March 2010. Total amount of solar insolation was 16,800kWh and total amount of heat collected was 5,870kWh. Thermal efficiency of solar collector in March was 35%.

Thermal efficiency is plotted as a function of {(Tc,out+Tc,in)/2-Ta}/I in Fig.7. At the high collecting temperature (at large value of (Tc,out+Tc,in)/2-Ta), efficiency of flat plate collector decrease while that of evacuate tube type heat pipe stable. It means evacuate tuype heat pipe collector is suitable for "Solar cooling" where absorption machine require relatively high temperature heat source water.

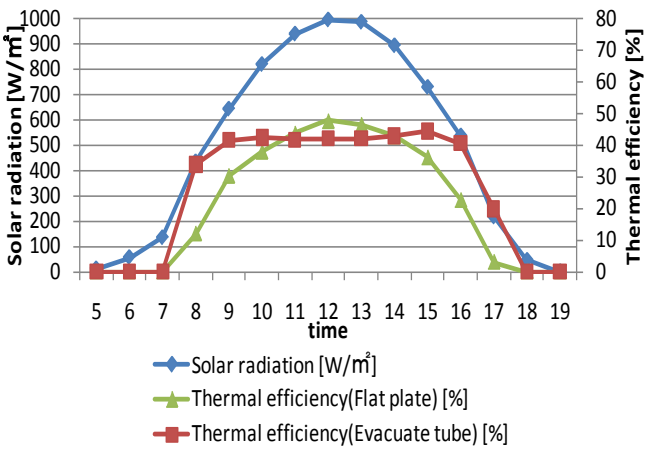


Fig.5 Collected heat and thermal efficiency of collector

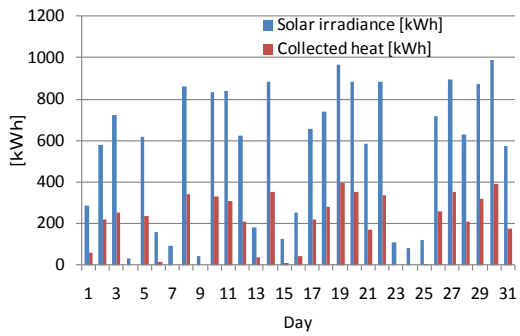


Fig.6 Daily solar irradiance and amount of heat collected (March, 2010)

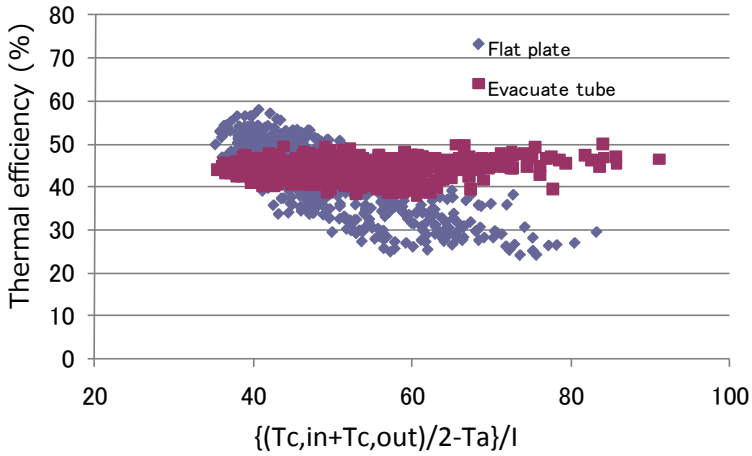


Fig.7 Plot of thermal efficiency as function of {(Tc,in+Tc,out)/2-Ta}/I

3.2 System performance in winter (heating)

Fig. 8 shows daily amount of solar heat and gas energy consumed for heating. Monthly solar fraction calculated by following equation was 19%. Seasonal performance of the system is shown in Table 2. Solar heat utilization efficiency is 72% and solar fraction is 13.1 for heating season. Also ratio of pump energy to amount of collected heat is 12%.

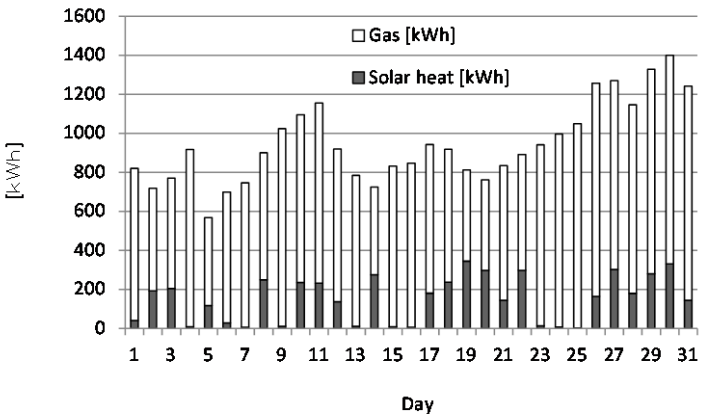


Fig.8 Daily amount of solar heat and gas energy consumed for heating

Table 2 Performance of system in heating season

		Feb.	Mar.	Apr.	Total
Collected heat	kWh	4,543	5,873	3,807	13,223
Heat delivered to heat exchanger	kWh	3,426	4,701	2,155	10,282
Heat loss	kWh	1,117	1,172	1,652	3,941
Pump energy (primary)	kWh	629	786	328	1,743
Solar fraction	%	8.3	16.0	25.5	13.1

3.3 System performance in summer (cooling)

Fig. 9 shows seasonal performance of the system for summer. Solar heat utilization efficiency changes among 78 to 89%. The highest heat utilization efficiency was seen in August. Fig. 10 shows . Monthly solar fraction calculated by following equation changes among 16 to 18%. In August, the coefficient of performance for system (System COP) and the saving rate of gas consumption were 1.4 and 0.1 respectively.

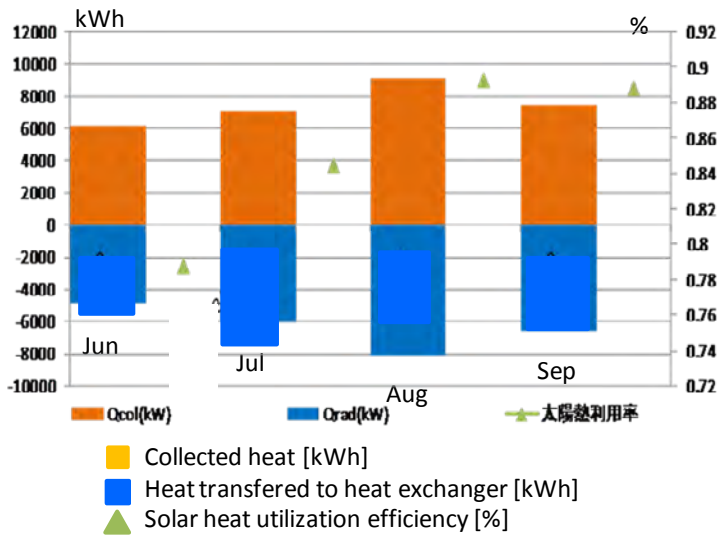


Fig. 9 Heat collected and transferred to absorption machine

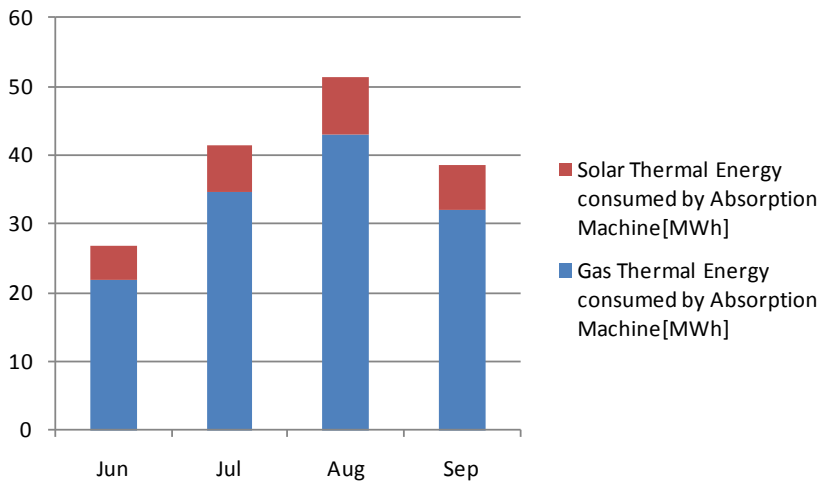


Fig. 10 Monthly amount of solar thermal energy and gas energy consumed for absorption machine

4. Simulation

In this paper, simulation of the performance of system in winter was conducted using LCEM tool. LCEM tool was developed by the basis of editorial supervision of Ministry of Land, Infrastructure and transportation, Japan for life cycle energy management of HVAC system.

4.1 Outline of Analysis Model

A part of LCEM tool Ver.3.02 was improved, and the simulation model was built. It consists of two models of the heat collection system shown in Fig. 11 and the air-conditioning system shown in Fig. 12. Two models are combined via interface.

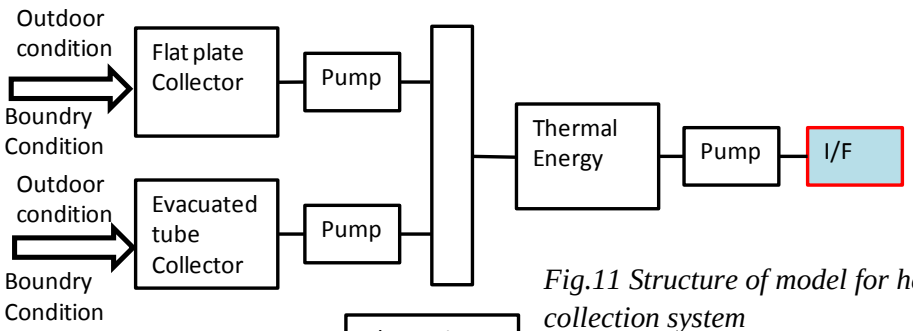
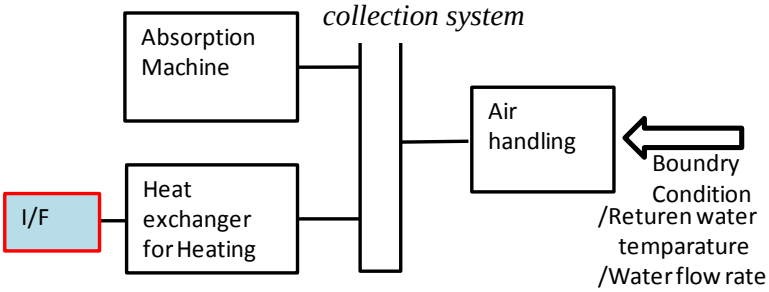


Fig.11 Structure of model for heat collection system



Fig,12 Structure of model for solar air-conditioning system

4.2 Collector Object

Heat collected by solar collector Qc (kW) is calculated by the following equations.

$$Qc = \eta * J * Ac \qquad (3)$$

Moreover, thermal efficiency of solar collector is expressed with the following equations.

$$\eta = \tau * \alpha - U * \triangle t / J$$

$$\triangle t = (Tc,in + Tc,out) / 2 - Ta \qquad (4)$$

The following characteristic were used in this simulation.

$$\text{Flat plate collector: } \eta = 0.578 - 0.00493 \triangle t / J \qquad (5)$$

$$\text{Vacuum-tube type: } \eta = 0.496 - 0.00156 \triangle t / J \qquad (6)$$

4.3 Thermal Storage Tank Object

The characteristic of thermal storage tank was assumed as complete mixed.

4.4 Pump Object

The energy consumed by pump is calculated using pump efficiency, water flow rate and head of piping system. Efficiency of pump is set constant in the object used in his paper. LCEM tool cannot make the model of the differential gap in the ON-OFF control of a pumps.

4.5 Heat Exchanger Object

The heat exchanger object used in this paper are as follows.

$$Qhex = C1 * (T1\ in - T1out) = C2 * (T2\ out - T2in) = \varepsilon * Qhexmax \qquad (7)$$

$$Qhexmax = Cmin * (T1\ in - T2in) \qquad (8)$$

$$\varepsilon = [1 - \exp\{-N(1-C)\}] / [1 - C\exp\{-N(1-C)\}] \qquad (9)$$

$$N = UA/Cmin \quad (10)$$

$$C = Cmin/Cmax \quad (11)$$

$$Cmin = 4.186*Wmin/60 \quad (12)$$

$$Cmax = 4.186*Wmax/60 \quad (13)$$

4.6 Absorption Chiller/Heater Object

The amount of gas consumption is assumed as the function of the load factor (q), and was modeled by the following formulas.

In case of 0% <q< 25%

$$G = 1.2*q/100*25.8 \quad (14)$$

In case of 25%<q<40%

$$G = (-0.013*q+1.533)*q/100*25.8 \quad (15)$$

In case of 40%<q<100%

$$G = q/100*25.8 \quad (16)$$

The differential gap in ON-OFF of absorption machine can not be expressed by LCEM tool and the outlet temperature was set to constant value of 55 degrees C.

5. Simulation Result

In this section simulation results for heating operation are shown. Fig. 13 shows the comparison between measurement and simulation for flat plate collector and evacuated heat pipe. Fig. 14 shows the heat collected and delivered to heat exchanger. Also fig.14 shows temperature in thermal storage tank. Fig. 15 shows the change of output of absorption machine. From these figures, it can be concluded that simulation results using LCEM tool shows good agreement with an actual measurement. However there are limitations of simulation as follows.

Time interval of calculation

In this study, 1 hour of time interval for calculation is applied. The system is controlled by the shorter time interval. Therefore, calculation result of collected heat at end of operation (evening) is overestimated. Also output of absorption machine (operate as boiler in heating) is overestimated when heat load is small. In this situation, absorption machine repeats operation and stop at short time step. However, this action cannot be expressed by simulation.

Simplified model

In this study, components in the system are modeled simply, for example heat loss from storage tank was neglected. This kind of simplification effects on the accuracy of simulation.

6. Conclusion

The system performance for the 1st year has been grasped by field measurements. Also system simulation for heating season was conducted by using LCEM tool. The simulation for cooling season will be conducted from now on. Although the system demonstrated good performance, improvement of operation should be conducted based on the results of field

measurements and simulation. Also simulation program will be revised to reduce the limitation which was mentioned in this paper.

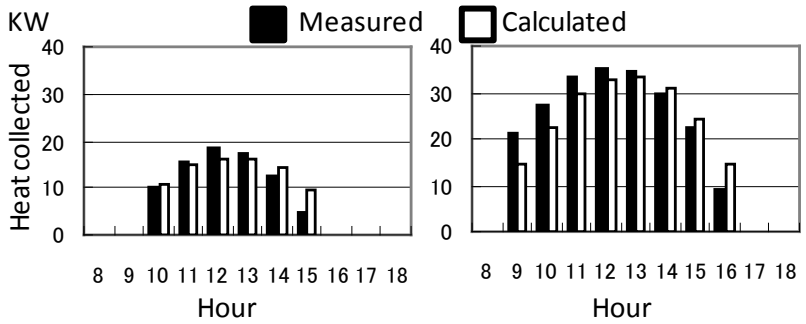


Fig. 13 Comparison collected heat by collector between measurement and simulation

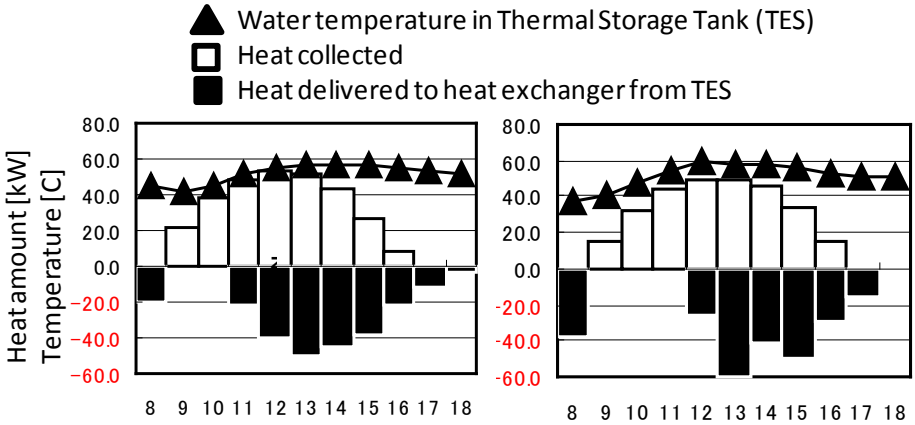


Fig.14 heat collected, heat delivered to heat exchanger and water temperature in thermal storage tank

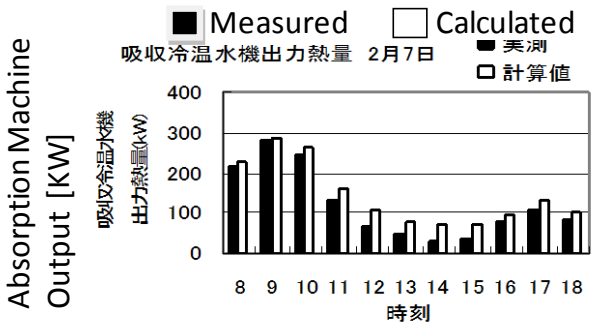


Fig. 15 Comparison of output of absorption between measurement and simulation

References

[1] N.Nakahara, K.Okada, H.Niwa, Study on System Applications of CPC Solar Collectors Part 4-Actual Operating Results of Solar Facilities for Chita Citizen's Hospital, SHASE Transactoin, No.33, 1987,pp61-73 (in Japanese).

[2] New Energy and Industrial Technology Development Organization, Japan, Design Guide for Solar Architectyre, 2001 (in Japanese)