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Performance assessment of solar assisted absorption heat pump system with parabolic trough collectors

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Abstract

A solar assisted absorption heat pump (AHP) system was installed in Tianjin University for space heating in winter and heat water supply. The primary heat source for the AHP is supplied from parabolic trough collectors. In this paper, experimental and simulation are presented to give an overview assessment of the whole system. The performance of the solar collectors in steady and transient state was investigated, the thermal efficiency curve that characterizing the optical and heat loss of the collectors was carried out with a series of tests. For the whole system, the absorption heat pump performance during operating test was measured and presented.
The simulation were performed by TRNSYS using the measured meteorological data and the estimated building load with the specific building type and structure, the daily and monthly operation showed that the solar radiation had significant impact on the ratio of useful energy provided by solar collectors, a high instantaneous solar fraction during the sunshine time while a very low average daily solar fraction was seen from the simulation results, this indicated that a thermal storage is necessary to improve the system performance and lower the auxiliary energy usage.

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Keywords: Absorption heat pump; Parabolic trough collectors; building load; solar fraction;

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Nomenclature

Q_u	useful energy gained by solar collectors	c_f	specific heat capacity of HTFs
m	mass flow rate of HTFs	A	total aperture area of collectors
DNI	direct normal solar radiation	ΔT	collector temperature difference between outlet and inlet
η	solar collector efficiency	θ	incident angle of solar collector (°)
$F_R(\tau\alpha)_\varepsilon$	intercept efficiency;	$F_R U_L$	efficiency slope
t_i	inlet temperature of solar collector	t_a	ambient temperature
Q_{th}	heating capacity of AHP	Q_{hw}	heat consumed by AHP

1. Introduction

Air quality in China is notoriously poor and recently has become an issue associated with increasing social unrest [1]. Ambient concentrations of total suspended particulates that exceed the normal levels are commonplace in most cities, especially in northern china due to the energy systems for heat supply are mainly based on the fossil fuel burning, such as boiler and heat network, which are of low energy efficiency as well as high air pollution.

The use of solar energy for building cooling and heating can potentially provide the solution to these economic and environmental problems [2], especially the solar assisted absorption heat pump (AHP) has drawn more attention due to its potential for use in sustainable energy and low environmental impact, and several works have been reported on the absorption unit and the integrated systems. Among the absorption working fluids, Sun et al. presented a review of working fluids for absorption cycles, the review reveals that $LiBr/H_2O$ and NH_3/H_2O (refrigerant-absorbent pair) are the most widely used [3]. Wei Wu et al. [4] had comprehensively summarized the thermodynamic and physical properties of ammonia-based and binary and ternary ammonia mixtures.

Single- and double-effect absorption machines are relatively mature as a marketable technology. For solar driving absorption systems, the driving heat source is mainly based on flat, evaluated, and compound parabolic trough (CPC) collectors which provide low temperature with a typical Coefficients of Performance (COP) range from 0.7 to 0.8 for single-effect absorption chiller [5]. Hammad and Zurigat [6] described the performance of a 1.5 ton solar cooling unit driven by a 14 m^2 flat-plate solar collectors, the maximum value obtained for actual coefficient of performance was 0.85. Ahmed et al. evaluated an integrated free cooling and solar powered single-effect lithium bromide-water absorption chiller, vacuum tube collectors of 108 m^2 aperture area was used, the results show that for sunny clear sky days with equal incident solar radiation, the daily solar heat fraction ranged from 0.33 to 0.41, collectors' field efficiency ranged from 0.352 to 0.492 and chiller COP varies from 0.37 to 0.81, respectively [7].

A solar thermal integrated cooling and heating system at Carnegie Mellon University was studied, this solar cooling and heating system incorporates 52 m^2 of linear parabolic trough solar collectors, a 16 kW double effect absorption chiller. Performance of the system has been tested, it was found that this solar thermal system could potentially supply 39% of cooling and 20% of heating energy for the building space [8]. Assilzadeh et al. [9] presented a solar cooling system using evacuated tube solar collectors, a model and simulation of the absorption solar cooling system was carried out with TRNSYS, and a typical meteorological year file is used to simulate the system.

Adnan et al. [10] investigated a prototype of an aqua-ammonia absorption heat pump system using a parabolic slote type collector to obtain a temperature of ~100 °C. Typical COP_h values of the AHP are in the range of ~1.5-1.8. The highest COP_h values are obtained at higher evaporator (10 °C) and lower generator temperatures (55 °C).

Argiriou et al. [11] developed a prototype low capacity (10 kW) single stage Li-Br absorption heat pump for floor heating/cooling, and a corresponding simulation model was presented to assess the overview of the performance of the complete system. The results showed that the estimated energy savings against a conventional cooling system using a compression type heat pump was found to be in the range of 20-27%.

Though several works have been dedicated to the study of solar absorption system, most of the research has focused on cooling and refrigeration through simulation or experiment, few systematic works concentrate on the heat pump cycle driven by medium temperature solar source which can produce hot water for heating and Domestic

Hot Water (DHW). In heating season, the climate and solar radiation will strongly affect the performance of the AHP cycle and system viability. This study aims to evaluate the performance of solar assisted absorption heating systems for building applications. The system operation was monitored, and the solar collector tests and the meteorological parameters are measured respectively. The TRNSYS software was used to model the dynamic property of the heating system with embedded the actual local solar radiation conditions.

2. System description

A solar assisted absorption heat pump pilot system in Tianjin University (TJU) was set up for space heating and heating water supply. The building functions as a scientific research office as shown in Fig. 1, which has a gross construction area of approximately 4000 m^2, with about 3000 m^2 demanding for space heating. The designed space heating load is 255 kW according to the local climate conditions. The integrated system consists of two loops: the soar collection loop and the variable load loop which meets the building's heating load, an auxiliary heater has been added to the system considering the variable climate conditions. The necessary instrumentation and control for the system have been installed to operate the system and to process the experimental data.

Fig. 1. The green building integrated solar assisted absorption heat pump in TJU.

2.1. Parabolic trough solar collector array

The solar collectors installed in TJU are single axis tracking solar concentrators: parabolic trough solar collectors (PTSCs). They track the altitude of the sun as it travels from south to north during the day to ensure that the radiation from the sun is continuously focused on the linear receiver. These PTSCs, provided by Vicot Air Conditioning Co., consist of five modules of parabolic reflectors in series and three rows in parallel, which have a total 225 m^2 aperture surface, Fig. 1 shows three arrays of PTSCs installed in series in the building roof.

2.2. Absorption heat pump

The system consists of 7 absorption heat pump units in parallel, with total heat capacity of 250 kW. NH_3/H_2O is the working fluid considering that the ambient temperature in winter is below zero. The cycling HTFs are connected with the generator of the heat pump directly. When the temperature of HTFs reaches up to 150 °C, the valves at entrance of absorption heat pump units open up, the high-temperature medium goes into the heat pump units and drives the heat pumps as high-temperature heat sources, the units work and produce hot water for heat supply. When the radiation intensity is not enough to heat HTFs to the setting temperature, the auxiliary heater shall start to fill up heat to ensure normal operation. The parameters of the collectors and the absorption heat pumps are summarized in Table 1.

Table 1. Parameters of the collector modules and absorption heat pump units

Parabolic trough collector modules		Absorption heat pump unit	
Collector length	6.1 m	Type	VSAH 040
Collector width	2.5 m	Working fluids	MR717
Collector height	2.8 m	Rated capacity (hot-water/heating)	38/42 kW
Unit aperture surface	15 m^2	Heat transfer medium	Synthetic oil
Concentration ratio	60	Heat source temperature	150-205 °C
Focal length	0.85 m	HTF flow rate	4 m^3/h
Tracking type	South to north	Hot-water/heating	50/35 °C

3. Experimental results and analysis

3.1. Solar collector thermal efficiency

The parabolic trough collector loop is the main heat source for the absorption heat pump, which significantly characterizes the performance of the system. To investigate the collectors, a steady state and transient state tests were carried out to evaluate the efficiencies. For steady state test, the HTF flow rate, ambient temperature, collector inlet temperature was strictly limited. To gain the similar test conditions, the tests were only carried out when direct normal solar radiation was above 800 W/m^2, and the average fluctuation was less than ± 50 W/m^2, and the ambient temperature changed below ± 1 K during test period. The steady state experiment was lasted several days. The collected data was processed by equation (1) and (2).

$$Q_u = c_f \cdot m \cdot \Delta T \tag{1}$$

$$\eta = \frac{Q_u}{A \cdot DNI \cdot \cos\theta} \tag{2}$$

$$\eta = F_R(\tau\alpha)_\varepsilon - F_R U_L (t_i - t_a)/DNI \tag{3}$$

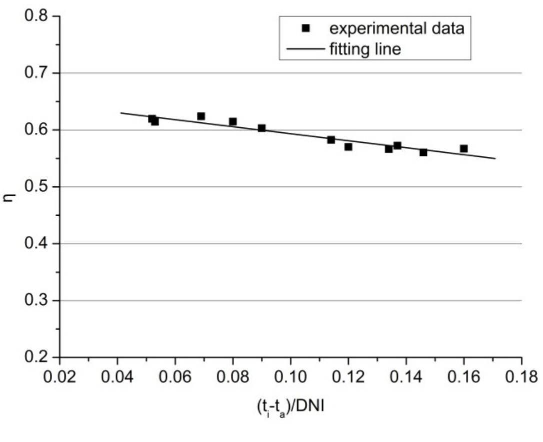


Fig. 2. The normalized efficiency of solar collectors

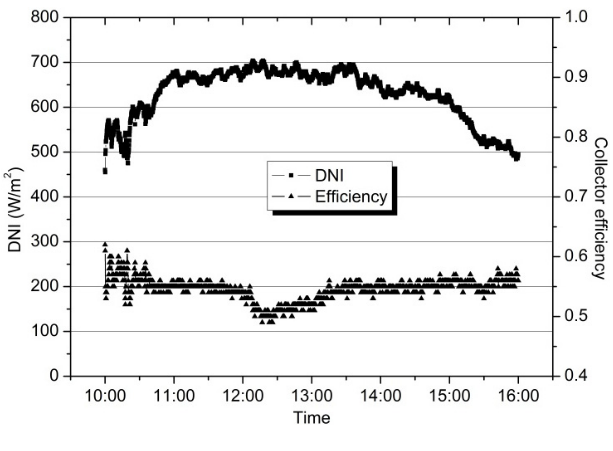


Fig. 3. Instantaneous collectors field efficiency

$$\eta = 0.6437 - 0.5430(t_i - t_a)/DNI \tag{4}$$

The steady and transient state experimental data of the collector efficiency were expressed as Fig. 2 and Fig. 3. From the experimental points of steady state, a statistical regression tool was introduced to generate the collector efficiency correlation based on equation (3), and the results were shown as equation (4). The intercept of the curve in Fig. 3 identified the constant optical efficiency of the collector, and the slope expressed the heat loss dependent on the operating temperature, and their heat capacity upon measurements obtained during periods of changing temperature. The instantaneous efficiency was sensitive to DNI, ambient temperature and wind speed. It was obvious that the efficiency smoothly decreased at 12:30 am because of some shadows due to a small adjacent top tower.

3.2. Heat pump performance

The integrated system consists of 7 absorption heat pump units, and each unit includes condenser, evaporator, absorber, generator, working fluid pump and expansion valve. NH_3/H_2O is used as the working pair. These heat pumps are driven by parallel heat source from PTSCs. The heat pump can not only produce heat water for space heating but also heat water, the two types of operating mode can be converted according to the program set.

In winter season, the absorption heat pump acts as a heater for space heating. Coefficient of heat pump (COP) that is defined in equation (5) is an essential parameter to evaluate the ability of the absorption heat pump. In different weather conditions and different operating mode, the COP varies significantly. The absorption heat pump unit was tested with different working conditions and illustrated in Fig. 4.

$$COP = \frac{Q_{th}}{Q_{hw}} \tag{5}$$

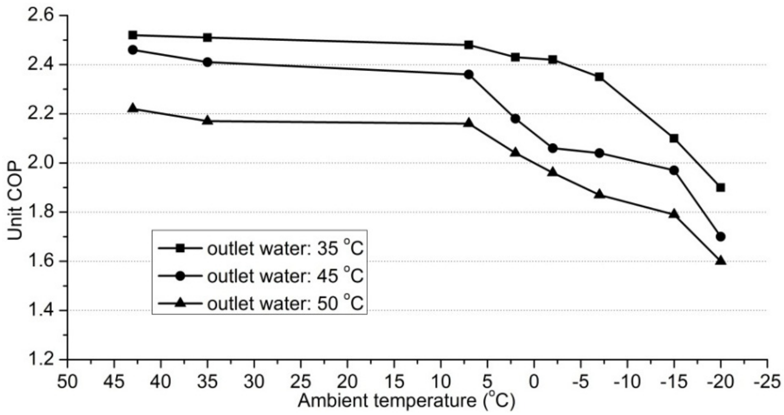


Fig. 4. Unit COP of heat pump at different working conditions

3.3. System test performance

In the beginning of the system operation, several days of test data were collected and monitored. The HTFs were circulated through the heat pump continuously. In the user side, water was used as working fluid relating to the condenser of heat pump and the end fan coil. The temperature from the collectors' outlet and in user side was not very stable since the system was under pilot run, and two days of measured data was chosen to present the analysis of the system performance. Table1 indicates the testing results of the heat pump system in working conditions.

Table 1. heat pump performance during operating test

Test #	Tambient (°C)	Average direct normal radiation (W/m^2)	inlet temperature in user side(°C)	Outlet temperature in user side(°C)	Measured heat load input (kW)	Measured heat load output (kW)	COP for the heat pump system

2013-11-20	6.6	358	47.5	48.8	48.5	90.5	1.87
2013-11-21	7.4	267	47.2	48.6	48.6	97.7	2.01

From the test, we can see that the temperature from the collectors and in user side is not very stable, because the system is only under pilot run, some parameters are not in their optimal range. The daily average results show that though the test was undergone at low solar radiation, the heat pump behaved good performance.

4. System performance model and results

4.1. System performance models

An overall solar building heating system performance simulation has been developed by TRNSYS. TRNSYS is an acronym for a 'transient simulation program' and is a quasi-steady simulation model, this program consists of various types of components, including solar collectors, heat pump, building load calculation, etc. There also have some subroutines that we can build the required components for system simulation. Fig. 6 shows the system simulation procedure. The measured meteorological data were used for the system model instead of the typical meteorological data, there were gained using the meteorological test platform in TJU, which could trace the real-time data and record automatically. The model of the PTSCs was validated by experimental data from the PTSCs performance tests. The hourly load of the building was estimated according to the specific building type, environmental conditions and ventilation situation.

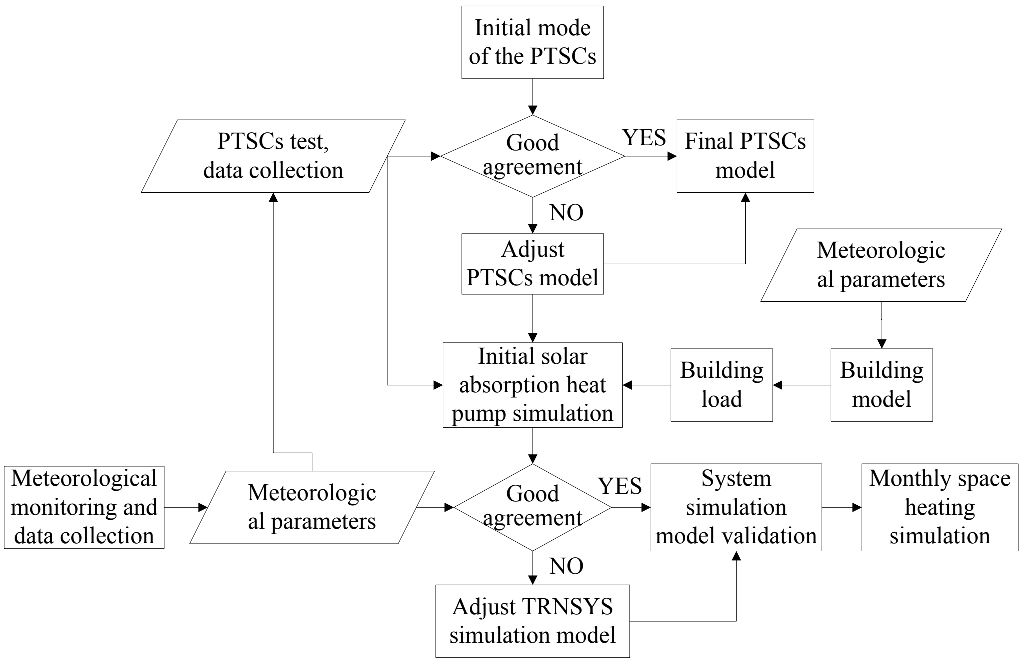


Fig. 5. System simulation flow chart by TRNSYS

4.2. Results and discussion

The developed simulation model is able to calculate the detailed operating conditions under various weather and output conditions and to search for an optimized system for long time operation. Several definitions assisted in understanding the performance of the solar heating system.

As the building in TJU is a scientific research office, considering the opening time of the building, the system working time was set from 8:00 am to 22:00 pm.

Fig. 6 and Fig. 7 demonstrated the daily average meteorological data collected and the estimated building load in December, respectively. The ambient temperature as shown in Fig. 6 expressed the building load for space heating, the lower the ambient temperature the higher the building load. Meanwhile, the daily direct normal solar radiation in the whole December varies significantly, fog appears in most days in TJ district, which affects the solar radiation and the PTSCs performance severely.

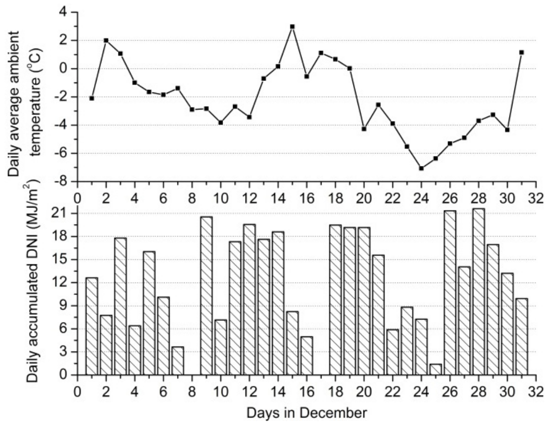


Fig. 6. Measured meteorological data in December

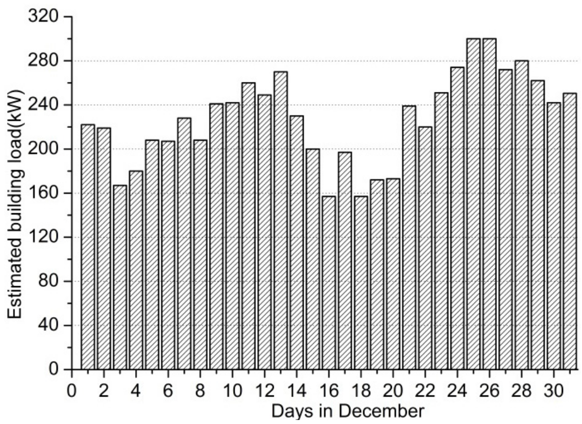
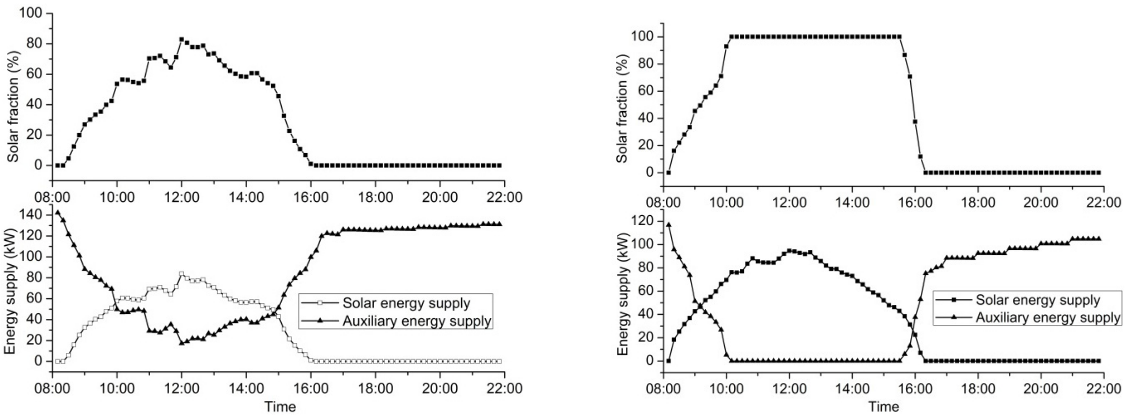


Fig. 7. Building heating load estimated by building simulation



(a) (b)

Fig. 8. Instantaneous energy supply and solar fraction: (a) cloudy day. (b) sunny day.

The results of daily transient system performance in two different weather conditions, cloudy and sunny day, were shown in Fig. 8. The collectors could not provide adequate heat for the heat pump due to the weak irradiation in cloudy weather as shown in Fig. 8 (a). However, in sunny day, the results in Fig. 8 (b) revealed that under good radiation conditions, the heat absorbed by solar collectors was abundant to the heat pump systems. So a heat storage system is necessary in order to store the extra energy in rich radiation situations.

Fig. 9 showed the daily performance of the solar heating system in evaluating the solar energy supply, the auxiliary energy supply, and the average daily solar fraction. The figure indicated that the average daily solar fraction was less than 50% in the whole December, this because the working time significantly affects the solar fraction. There exist several hours in a day that the building energy requirements are supplied by auxiliary energy completely because of the sun set and lacking of any other storage tank. For further improving the system performance and economy, better control and operating strategies need to be developed and optimized.

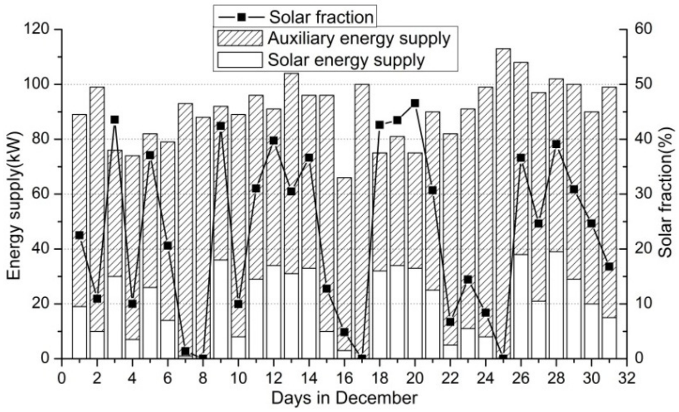


Fig. 9. Energy supply and daily solar fraction in December

5. Conclusion

Performance evaluation of a solar assisted heat pump system has been presented in this paper. The test of parabolic trough collectors has shown that a 50-60% thermal efficiency is maintained under different climate conditions, and the heat pump has a good heating performance though the system is under test. The established simulation shows that a high instantaneous solar fraction during the sunshine time while the daily average solar fraction is not exceeded 50%, this indicates that a thermal storage, better control and advanced operating strategies are necessary to improve the system performance and lower the auxiliary energy usage.

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