TEST REPORT OF SOLAR COOLING AND HEATING SYSTEM FOR THE INTELLIGENT WORKPLACE

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Table of Contents

List of Figures

List of Tables

1 Solar absorption cooling and heating test system and program

A solar absorption cooling and heating test system has been designed, installed, and tested in the Intelligent Workplace (IW) at Carnegie Mellon University in Pittsburgh. As shown in Figure 1, the system consists primarily of 52 m^2 of parabolic trough solar collectors, PTSC's; a 16 kW double effect absorption chiller; a heat recovery exchanger; and a variable load, simulated building load exchanger to measure the performance of solar collector and the overall solar cooling and heating system. The system has two loops: the solar collection loop with its three parallel branches and the load loop. The solar collection loop comprises the PTSCs, the absorption chiller; the heat recovery exchanger, HX-2; a bypass line extending from the three-way valve; an expansion tank, TK-1; and two main circulation pumps, S1 and S5, serving the chiller and HX-2, respectively. As one of major system components, the specification of PTSC given by Broad Air Conditioning is shown in Table 1. The load in the load loop is provided by a shell and tube heat exchanger, HX-1, fed with heated or chilled water from the campus grids for cooling or heating tests, respectively. A web based data acquisition and control system was developed and installed to operate the solar system and to store and display the test measurement data.

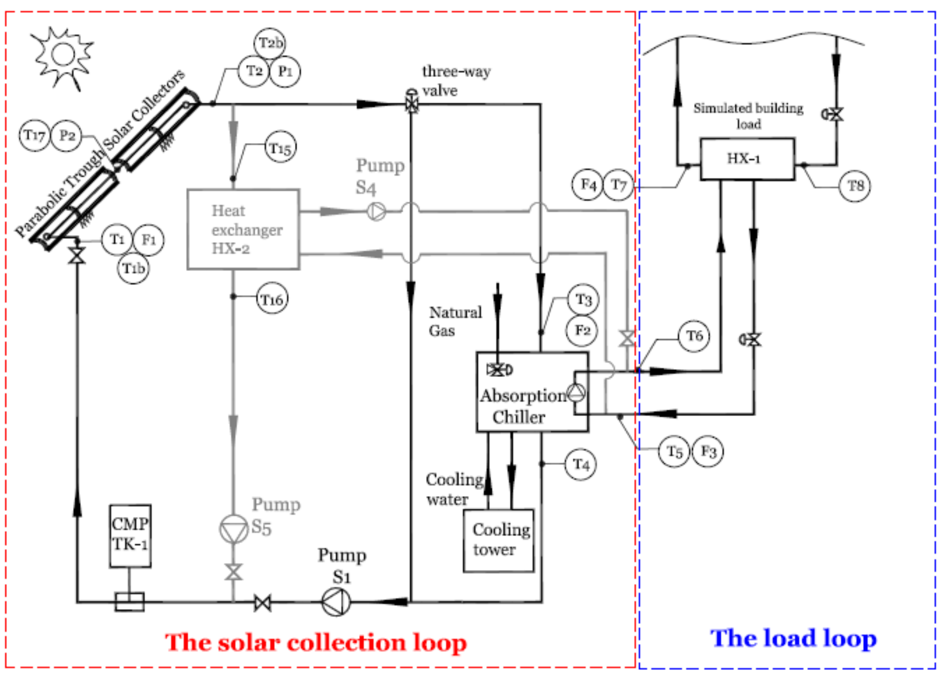

Figure 1. P&I Diagram: the Solar Building Cooling and Heating System

Parabolic trough solar collector features (BJ16A)	
Manufacturer:	Broad Air Conditioning Broad Town, Chang Sha, Hu Nan, CHINA
Operating temperature:	60-180C
Module size:	2.3 X 5.75 m; 13.225 m^2
Module operating weight:	200 kg
Drive group size:	2 modules; 26.45 m^2
Delta-T loop size:	2 drive groups; 52.9 m^2
Rim angle, 1:	73°
Reflectors:	Typical reflectance 0.8
Focal length:	81.8 cm
Receiver:	Absorber OD: 3.8 cm Base material: Stainless steel 304L Coating: Black nickel Typical absorptance: 0.96 Typical emittance: 0.14@100C Pyrex glass cover OD: 10.2 cm Transmissivity: 0.91 Vacuum in the annular space
Sun tracking	Single-axis elevation tracking based on the calculated sun position
Tracking drive System	24 V powered Servo motor Small gear, big gear.
Wind loads	16 m/sec (tracking) 31 m/sec (stowed)

Table 1. Parabolic Trough Solar Collector Specification from Broad

The PTSCs were tested at various operating conditions: different direct solar irradiation; wind velocity; heat transfer fluid, HTF, flow rate; operating temperature. Daily tests on the solar cooling and heating were conducted at various weather conditions in winter and summer. In the future, this solar absorption cooling and heating test system will be integrated with the cooling and heating units of the IW and the campus cooling and heating grids.

[1] Rim angle is the angle between the line from vertex to focus and the line from focus to the parabola ridge point.

2 The test program

The test program was planned, and then conducted in 37 days from February to September of 2007. The weather conditions for the tests included clear days, mostly sunny days, mostly cloudy and overcast days in both winter and summer. There were four varieties of tests used to evaluate the PTSC and the system performance: PTSC tests at transient states, PTSC tests at a steady state, solar absorption cooling/heating tests using the absorption chiller, and solar heating tests using heat recovery exchanger, HX-2. The operating temperature, operating system, and the number of days for these tests are listed in Table 2.

Test name	days	Operated system	HTF temperature operated (˚C)
PTSC test at transient states	10	Solar + HX Solar + Chiller	10 -180
PTSC test at a steady state	17	Solar + HX Solar + Chiller	0 - 98 ; 19 - 162
Solar absorption cooling / heating daily test	16	Solar + Chiller	0 - 164
Solar heating daily test by using heat exchanger	2	Solar + HX	0 - 93

Table 2 Four Variety of Tests Conducted

- PTSC test at transient states

In this type of the test, the HTF was heated in the PTSC's and circulated through the by pass or the heat exchanger, HX-2, in the solar collection loop as shown in Figure 2. The PTSC's were operated in a transient state in which the operating temperature of the solar increased with time due to the solar heat gain.

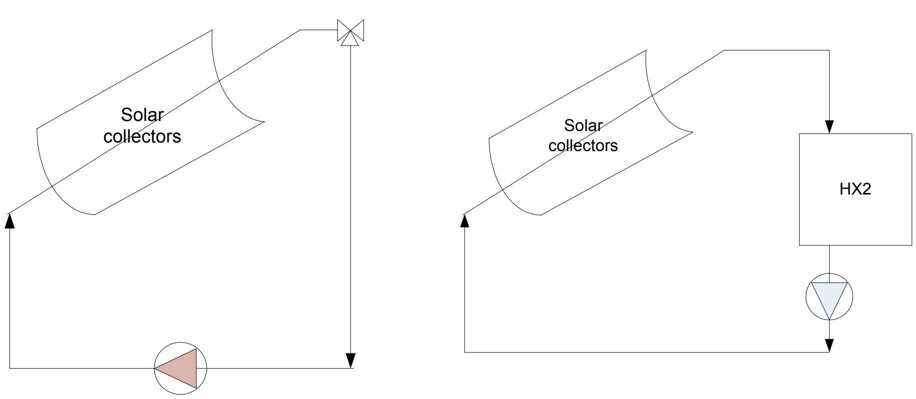

Figure 2 PTSC Test Diagram in the Transient State

The operation ceased when a critical temperature, the maximum operating temperature specified by Broad, was researched. The data from this type of test was used in the determination of the optical efficiency, the heat capacity, and the heat and pressure losses of the PTSC's and the balance of the system.

- PTSC test at a steady state

In these tests, as in the transient state tests, the HTF was heated in the PTSC's and circulated through the by pass or HX-2 at the beginning of test, until the desired elevated temperature was reached. Then the HTF was switched to flow through the absorption chiller or through the heat recovery exchanger HX-2 and the pump S5. A building load was simulated by the load exchanger HX-1 and was adjusted to maintain the solar loop at a near constant operating temperature, a quasi-steady state. The quasi-steady state refers to the condition of the collector when the flow rate and inlet fluid temperature are constant, but the exit temperature changes slightly due to the normal variations in solar irradiance that occur with time for clear sky conditions. If the steady state became difficult to maintain due to the heat loss of system and the reduction of solar radiation, the operation was halted. This kind of the test, as illustrated in Figure 3, is used to determine the performance of solar collector.

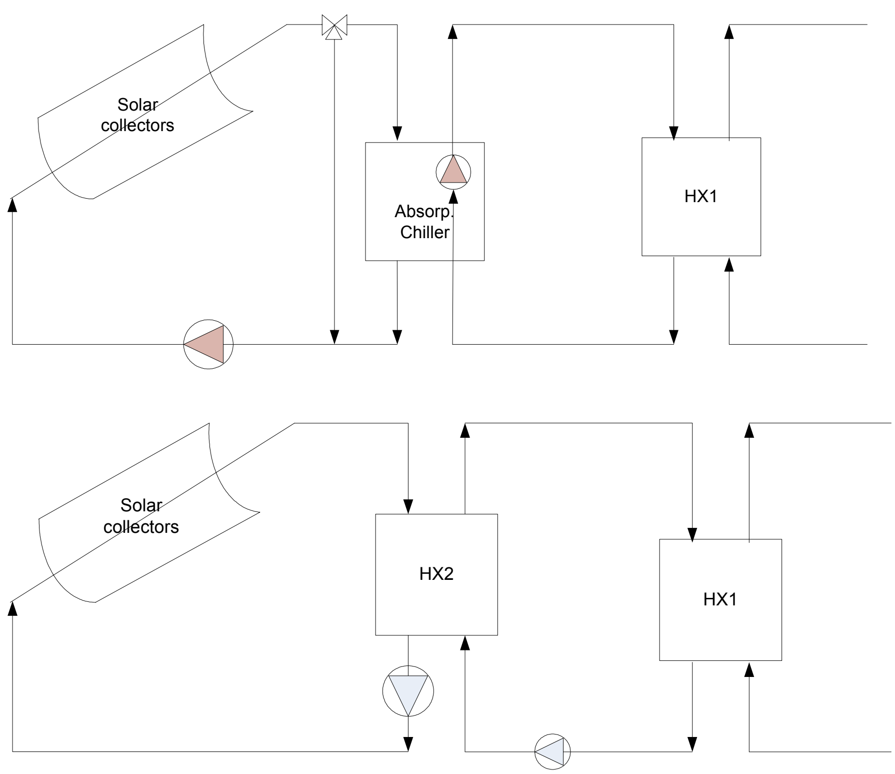

Figure 3 PTSC test at a steady state

- Solar absorption cooling / heating daily test

In these tests, when the desired HTF temperature was reached, the HTF was diverted to absorption chiller to produce chilled water or heated water for space cooling or heating. The simulated building load was modified to maintain the temperature of the chilled water or heated water from the chiller within a reasonable range by regulating the flow of heated water or chilled water from the grids of the building flowing through the load exchanger, HX-1, as indicated in Figure 4. Finally, when amount of solar energy supply was no longer adequate to operate the chiller due to the heat loss of system and the reduction of the direct normal solar radiation, the HTF was switched back through the by pass.

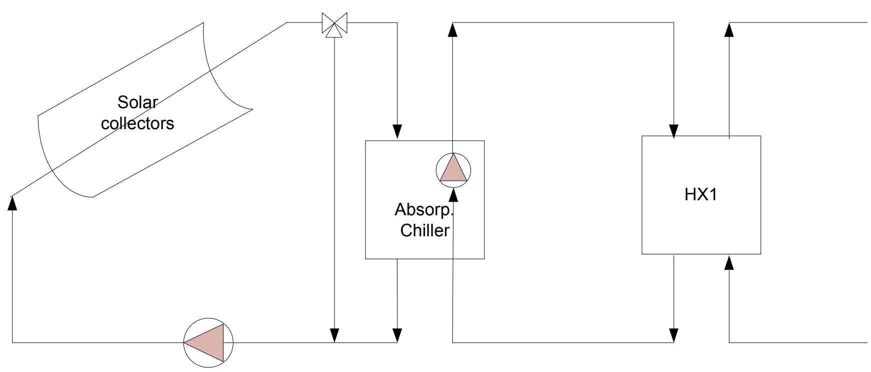

Figure 4 Solar Absorption Cooling/Heating System Test

- Solar heating test using heat recovery exchanger, HX-2

In these tests, the HTF was circulated and heated through HX-2 without running the load pump, S4 on the cold side of the exchanger until the desired operating temperature was reached.

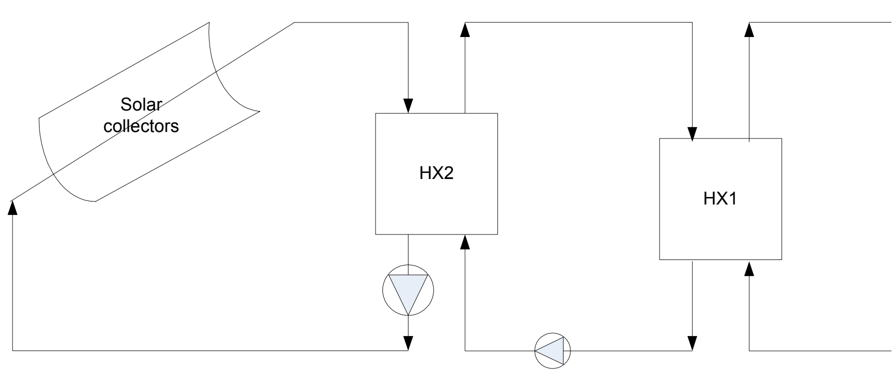

Figure 5 Solar heating daily test by using heat exchanger

Then HX-2 was used to provide heat to the load exchanger, HX-1 by operating the load pump, S4. The simulated building load was modified to maintain the hot water from HX-2 within a reasonable range by regulating the flow of chilled water flowing on the cold side of the HX-1, as shown in Figure 5. Finally, when amount of solar energy supply was no longer adequate to operate HX2 due to the heat loss of system and the reduction of the direct normal solar radiation, the system operation was halted.

Overall, the purpose of the solar thermal building cooling/heating test program is to determine

- operating conditions such as temperature, flow rate and pressure of the HTF in the PTSC's and the system in various situations.
- the characteristics of the PTSC's: their optical and overall efficiencies, heat capacity, heat and pressure losses over a range of operating conditions..
- the performance of the absorption chiller: its capacity and COP for both cooling and heating, depending on the operating conditions.
- the time required for the PTSC's and the system to reach a desired operating temperature.
- the characteristics of system, such as heat capacity and heat and pressure losses
- the potential of solar thermal energy for space cooling/heating in a building.
- the choice between the chiller and the heat recovery exchanger HX-2 as representing the most effective system for heating.
- possible design and operational measures for improving the performance of the PTSC's, the chiller, and the overall solar thermal cooling/heating system.
- techniques for the design of such systems for optimal, economic performance.

The data acquisition system gathered the data of direct normal solar radiation, temperature, pressure, and flow rate throughout the system. Samples of the gathered data for use in analyzing the performance of the PTSC's and the solar building cooling/heating system follow.

3 Experimental results

3.1 PTSC test at the transient states

The PTSC tests at transient conditions were conducted by focusing the PTSC's, heating the HTF to a desired temperature without rejecting heat, and then defocusing the PTSC allowing the HTF temperature to drop. This process has been repeated under various flow rates, starting times during a day, and ambient temperatures.

Experimental data from a test on March 29, 07, typical T-t and Q-t charts from this kind of tests, are shown in Figures 6 and 7. These charts show that the HTF temperature was nearly uniform in the solar collection loop during the heating period. In addition,

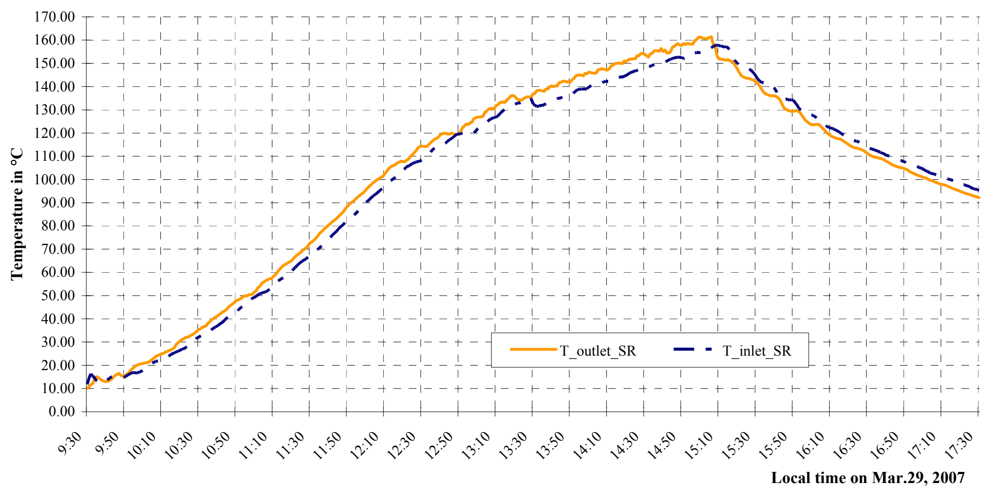

Figure 6 Operating Temperatures from the PTSC Test at Transient State on 29 March2007

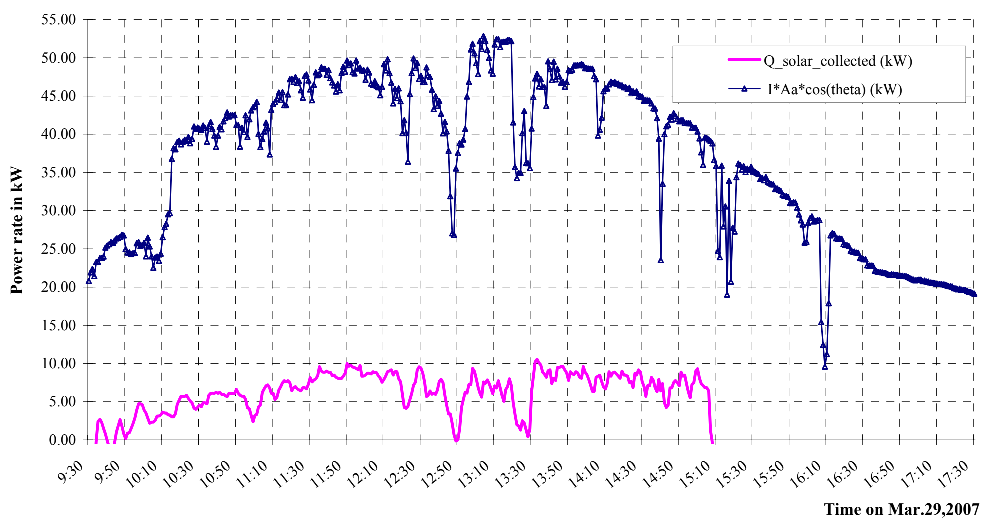

Figure 7 Energy Quantities for the PTSC Test at the Transient State on 29 March 2007

after the PTSC was defocused, the HTF at the outlet of the PTSC was lower than one at the inlet. due to the heat losses from the receiver to the surroundings.

3.1.1 System heat capacity test

The PTSC's heat capacity determines the amount of energy and thus the time required to raise the temperature of the HTF circulating through the system to a desired operating value during the system warm up. Since thermal losses can confound measurements of the PTSC's thermal capacity, a special test was performed under conditions that minimize such losses.

The test used chilled water and heated water from campus grids: the PTSC's are not focused. First, the HTF was circulated through the heat recovery exchanger, HX-2, in the solar collection loop and cooled by rejecting heat to chilled water from grid through the cold side of the test load exchanger, HX-1, until its temperature was lowered to a value 5 - 15 ˚C below the ambient temperature. Next, a stream through of heated water from the building grid replaced the chilled water circulating through HX-1. The HTF was heated by this source until its temperature reached a value 5 - 15 ˚C higher than ambient temperature. The test was then halted. It was assumed that the net exchange of heat between the system and the ambient surroundings in these two process steps was nil. The heat capacity of the system was calculated by dividing the total heat transferred from and to the HTF in HX-2 in these two process cooling and heating steps by the difference between the maximum and minimum HTF temperatures. The test basically included two processes: cooling and heating. The system heat capacity was also calculated from the masses and specific heats of the PTSC's, the exchanger, the pipe, and the HTF fluid they contain. Table 3 shows good agreement between the measured and the calculated values of the total heat capacity of the system.

Test #	$T_{ambient}$ (˚C)	Measured heat capacity (kJ/˚C)	Calculated heat capacity (kJ/˚C)
1	25.5	697	576~629
2	24	711	
3	28	576	
4	25	611	

Table 3 Heat Capacity of the Solar Loop

3.2 The PTSC tests at a steady state

The PTSC tests were performed only on clear days when the direct normal solar radiation was greater than 630 W/m^2, and its variability was less than $\pm 4\%$ throughout the tests. Since wind velocity greatly impacts the convective heat loss from the PTSC's, all of performance tests were performed with wind speed less than 4.5 m/s. Turbulent flow was maintained within the absorber pipe to ensure good heat transfer between the fluid and the pipe. In the various tests, either the absorption chiller of the heat recovery exchanger, HX-2, were involved.

The operating temperatures of HX-2; the pump, S4; and the temperature sensors T5 and T6 are limited to those lower than 107 ˚C. To test higher operating temperature in the PTSC's, the absorption chiller was used. The PTSC tests have been conducted in 17 clear days in the period February to July 2007. The ranges of operation conditions are listed in Table 4.

$T_{ambient}$ ˚C	Wind m/s	T_{inlet} ˚C	$FR_{solarloop}$ gpm	Reynolds Number	Incident Angle	Direct Normal Solar Radiation, W/m^2
-2.5 ~ 29.28	0.42 ~ 3.23	41.5 ~ 151.2	5.6 ~ 8.4	6541~49979	3 ~56	651 ~ 997

Table 4 Operating Condition Ranges in the PTSC Performance Tests

Figure 8 and 9 are the experimental temperature-time, and energy rate-time data from a typical PTSC performance test at a steady state on 22 April 2007. The plots show the temperatures at the inlet and outlet of the PTSC's and the two heat exchangers, HX-2 and HX-1. The time step for the measurements was 1.0 minute. During the test period, three quasi steady states were established for which the PTSC performance was calculated. .

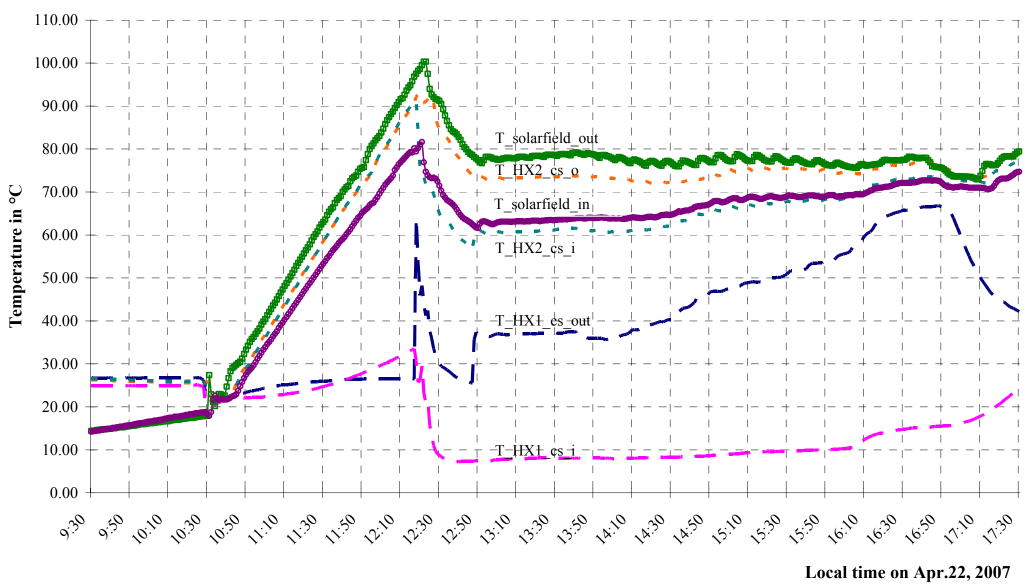

Figure 8. Operation Temperatures for a PTSC Test at 3 Steady States on 22 April 2007

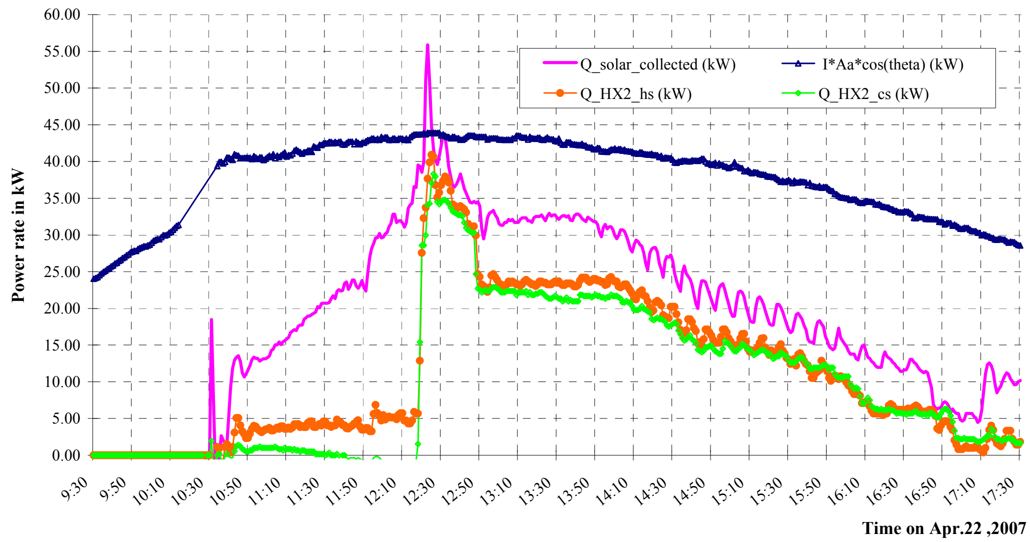

Figure 9. Energy Rates for the PTSC Performance Tests on 22 April 2007

3.3 Solar tests with the absorption chiller for cooling/heating

Solar tests with the absorption chiller, cooling/heating, were conducted during clear or mostly clear days in Pittsburgh throughout a year. The operation proceeded normally from morning startup to shutdown in the evening or until terminated by the appearance of clouds. The experimental data from these cooling/heating tests were used to characterize the PTSC's, the absorption chiller, and the overall system. This performance information is the key in determining the overall effectiveness of the solar system in providing cooling and heating for the building throughout a year.

3.3.1 Solar absorption chiller cooling daily test

Solar cooling tests with the absorption chiller have been performed in thirteen days from June to August 2007. The weather conditions changed rapidly during this period, and it was difficult to achieve stable direct normal solar radiation throughout a day. The experimental data, shown in Figures 10 and 11, show that about three hours are required to heat the system from the ambient temperature to 160 ˚C, the temperature at which the absorption chiller was programmed to switch from natural gas to solar energy for operation. The absorption chiller operated about four hours on the available solar energy during this sunny day in Pittsburgh. After 16:30, the PTSC's could not provide HTF at a temperature high enough to operate absorption chiller efficiently.

The HTF loop from the solar field then bypassed the absorption chiller; and natural gas burner was required to operate the chiller.

Experiments in three of thirteen days provided reasonable data on system performance for solar cooling. Figure 10 through 13 show system temperatures and heat energy quantities for cooling operation throughout two days in July 2007. Figures 10 and 11 show throughout a day, the measured temperatures of the HTF at the exit of the PTSC's and at the inlet and outlet of the chiller and also of the chilled water at the inlet and outlet of the chiller. The rapid rise of the temperatures of the HTF at the chiller inlet and outlet was the result of the three way valve opening to admit the HTF to the chiller when its temperature exceeds 160˚C. Prior to this time, the chiller was heated by the flow of natural gas to the regenerator. Figures 12 and 13 show these corresponding calculated heat quantities:

- the solar input; the product of direct normal solar irradiation from pyrheliometer measurements, actual aperture surface area, and the cosine of the incident angle
- the delivered thermal energy to the chiller: the product of the HTF flow and the temperature difference over the chiller.
- the cooling capacity provided by the chiller: the product of the chilled water flow and the temperature difference over the chiller.

As indicated by these figures, when the HTF was operated at 150 ~ 160 ˚C, the overall solar efficiency of the PTSC's was approximately 33% to 37%. The COP of the installed absorption chiller was in the range 1.0 to 1.2. The solar COP of the overall installed solar cooling system, the product of the COP of absorption chiller and the solar collector efficiency, was therefore about 0.33 to 0.44.

The maximum capacity of the absorption chiller was 12 kW. One of the reasons for this capacity, significantly lower than the chillers design capacity of 16 kW, was related to the weather conditions in Pittsburgh. Since it was very humid, the direct normal solar radiation was not high, typically about 600~900 W/m^2.

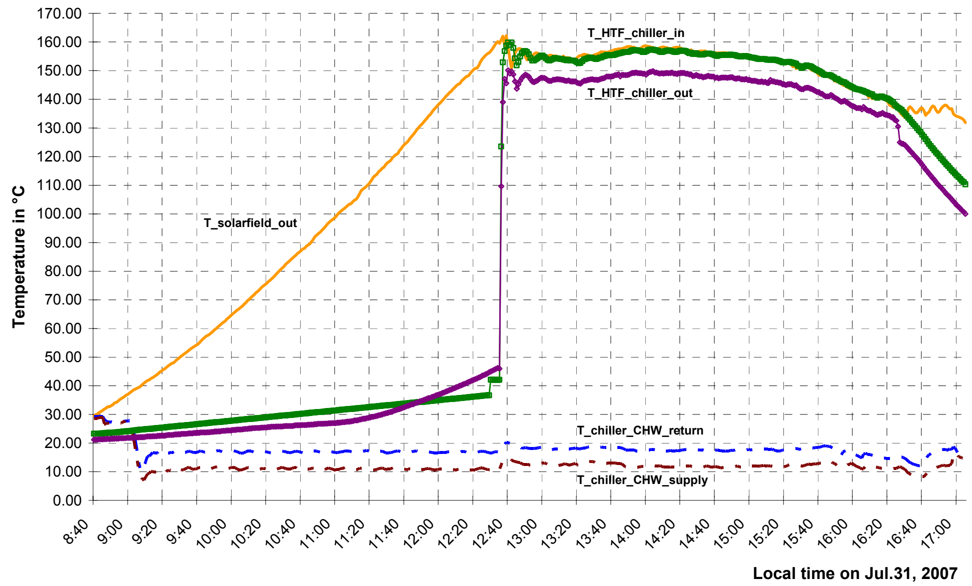

Figure 10 Operating Temperatures of the Solar Cooling Test 31 July 2007

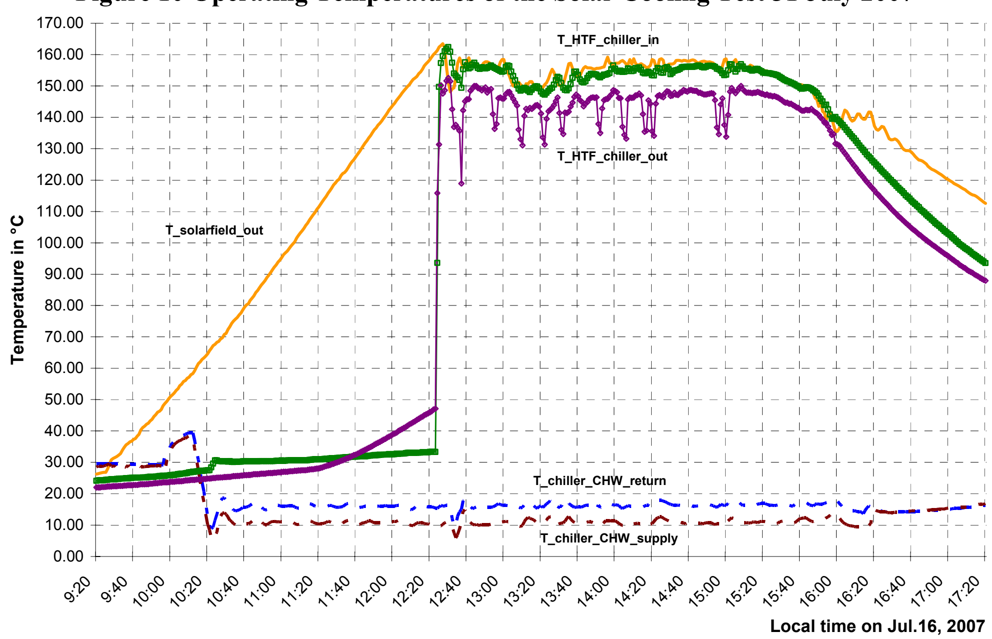

Figure 11. Operating Temperature of Solar Cooling Test on 16 July 2007

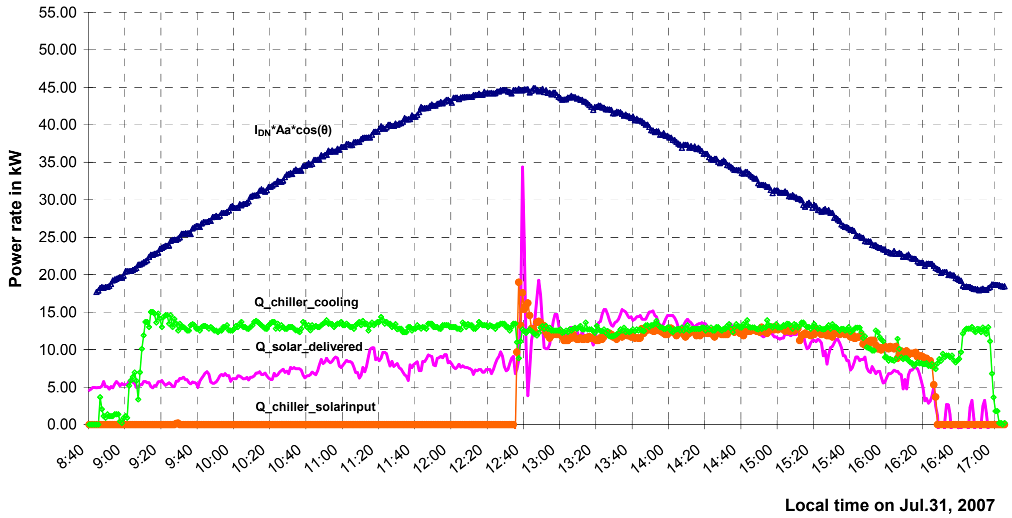

Figure 12 Cooling Capacity of the Solar Cooling System on 31July 2007

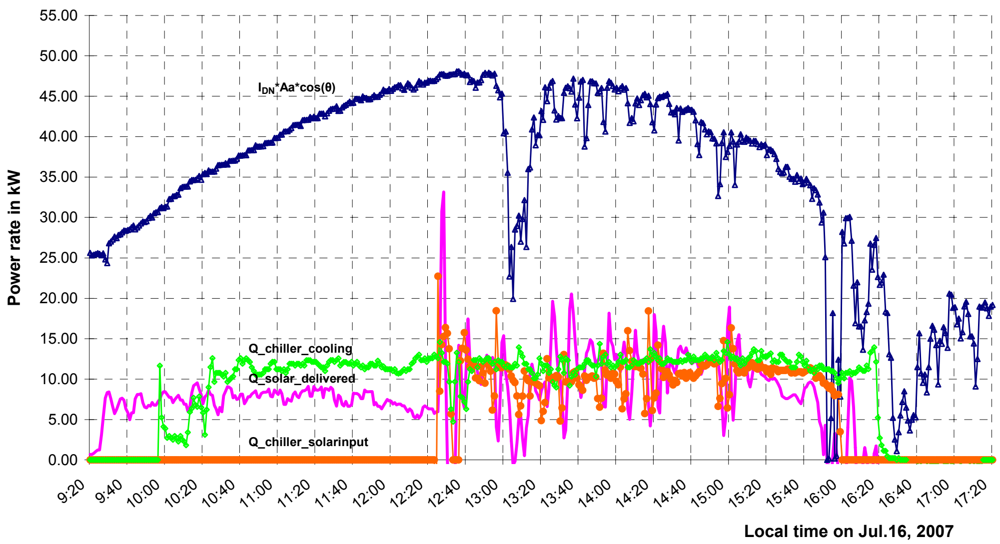

Figure 13 Cooling Capacity of Solar Cooling System on 16 July 2007

3.3.2 Solar absorption chiller heating daily test

Solar heating tests using the absorption chiller have been carried out in three sunny cold days from February to April 2007, during which weather was still cold, about 0 ˚C. Following the procedure outlined of for the solar absorption cooling tests, the HTF, the propylene glycol solution, was heated in the PTSC's, circulated through the regenerator of absorption chiller and then returned to the PTSC's. The heated water produced in the evaporator of the chiller was circulated to the load test heat exchanger, HX-1.

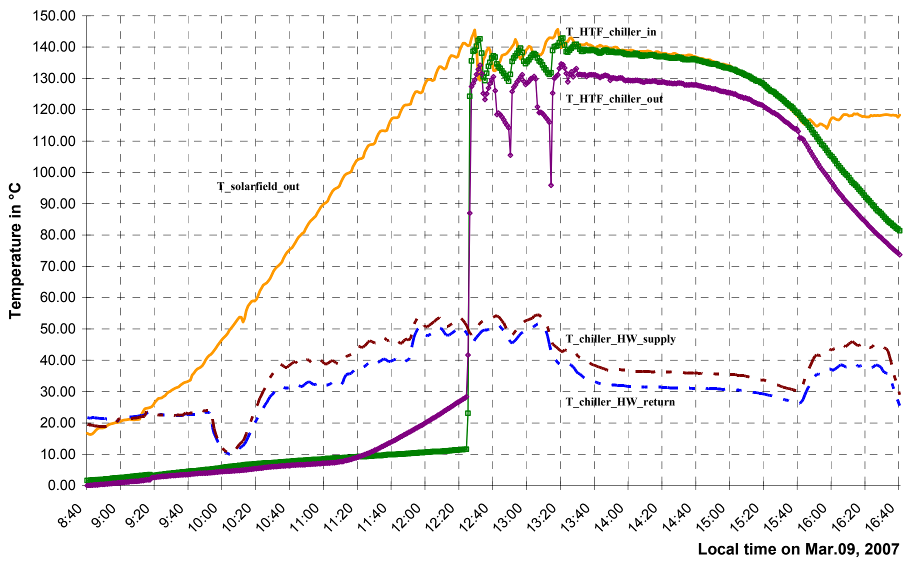

Figure 14. Operating Temperatures of the Solar Heating Test with the Chiller 9 March 2007

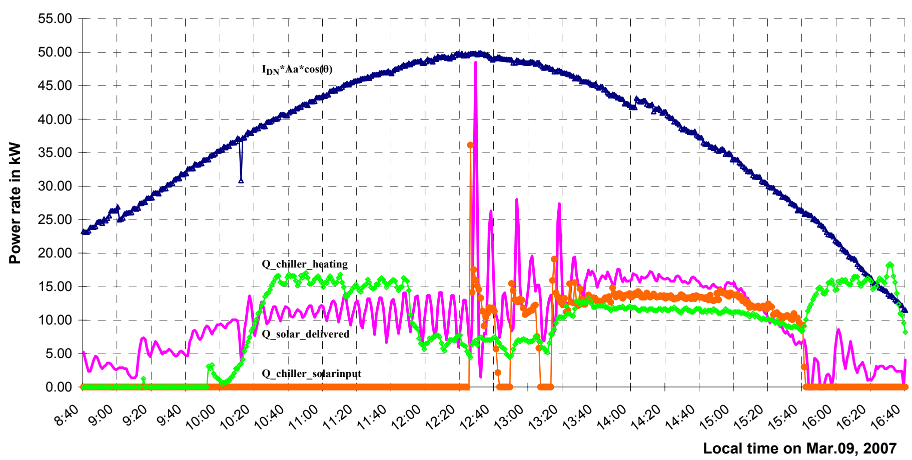

Figure 15 Heating Capacity of Solar Heating System with the Chiller on 9 March 2007

In order to ensure adequate heat transfer in the PTSC's, the flow of the HTF was set at a value that ensured turbulent flow in the absorber pipe throughout the tests.

Similar to the curves presented above for cooling with the solar absorption chiller, Figure 14 and 15 show, the measured temperature and heat flow quantities throughout the day for 9 March 2007. The charts show that the heat delivered by the system was about 12 kW, when the hot water was produced by the chiller at 37 ^{o}C, some 20 ˚C lower than the rated supply temperature, 57 ˚C. If hot water was produced at 52 ^{o}C by increasing the entering temperature to 50 ^{o}C, some 15-18 kW energy input was required; the heating efficiency was significantly reduced. Reasons for this reduced heat efficiency of the absorption chiller may be the increased thermal losses to the surroundings during the condensation process in the evaporator and direct absorption of water vapor produced in the regenerator by LiBr solution in the evaporator.

3.4 Solar heating daily test by using heat exchanger

Solar heating tests making use of the heat recovery exchanger HX-2 have been carried out in three sunny, cold days from February to April 2007. Experimental data have been obtained to compare the system performance in solar heating using either the absorption chiller with the HTF at 140°C, as reported above, or the heat recovery exchanger with the HTF at 68 °C

Figures 16 and 17 are the experimental results of a solar heating daily test using HX-2 on 2 March 2007.

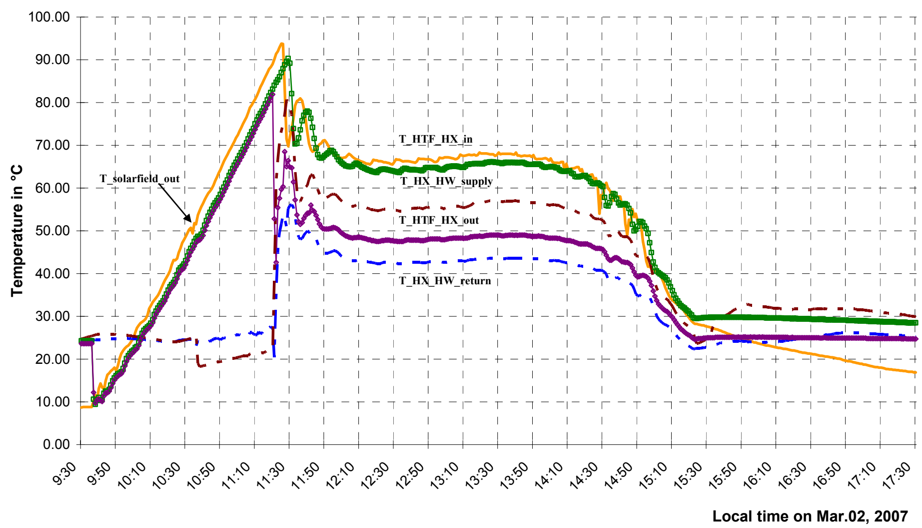

Figure 16 Operating Temperatures of the Solar Heating Test by HX-2 on 2 March 2007

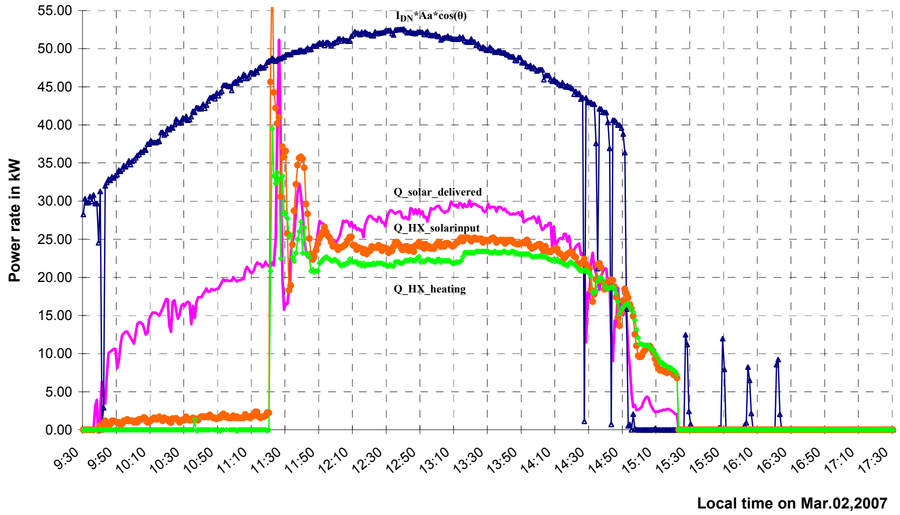

Figure 17 Heating Flows in Solar Heating system by the Heat Recovery Exchanger, 2 March 2007

As shown in Figure 16, HTF flow through the heat exchanger was initiated when the outlet temperature of the collectors reached 90˚C; this temperature dropped to 68˚C and remained stable as heat was delivered to the water stream flowing through the heat exchanger.

An comparison of solar heating using an absorption chiller or a heat recovery exchanger, based on the tests, presented in Table 5, shows clearly that a heat recovery exchanger is more effective. Use of the exchanger avoids the large temperature difference between the HTF and the heated water in the absorption chiller. And it allows the collectors to be operated at a lower temperature, thus reducing heat losses from the system.

	Solar + HX heating	**Solar + absorption chiller heating**
Q_useful (kW)	16 ~29	15~19
Operation hours (hrs/day) in March	5	2
Storage is possible	yes	not quite

Table 5 Comparison of Solar Heating Using the Heat Recovery Exchanger or the Absorption Chiller

4 The PTSC efficiency

The experimental data obtained from the Broad PTSC's were analyzed by inserting them in the overall energy balance equation for these receivers. Statistical regressions were performed to identify their constant optical efficiency, their heat loss dependent on the operating temperature, and their heat capacity based on measurements obtained during periods of changing temperature.

The overall solar collector efficiency of the PTSC's, dependent on their optical efficiency and heat losses, can be calculated for steady state operation by Equation 1.

$$\eta = \frac{\dot{m} * (C_{p\_out} T_{out} - C_{p\_in} T_{in})}{I_{DN} * A_a * \cos(\theta)}$$ **Equation 1**

where,

η = the overall solar collector efficiency

I_{DN} = direct normal solar radiation, in kW/m^2

A_a = aperture area of the solar trough, in m^2

θ = incident angle, degree

$\dot{m}$ = HTF flow rate through the PTSCs

C_{p_out}, C_{p_in} = specific heat of HTF at the outlet, inlet of the PTSCs

T_{out}, T_{in} = HTF temperature at the outlet, inlet of the PTSCs

Empirical relations are frequently provided for the η of PTSC's based on their optical efficiency, α, and their heat loss dependent on their operating temperature. Such equations are shown in Equations 2, based on a linear relation of heat loss with temperature, and Equation 3 using a second order relation. Actually the heat losses by conduction and convection from the PTSC's are expected to be linear with the operating temperature; but the heat loss by radiation to the surroundings, proportional to the fourth power of the operating temperature.

$$\eta = \alpha - \beta * \frac{\Delta T}{I_{DN}}$$ **Equation 2**

$$\eta = \alpha - \beta * \frac{\Delta T}{I_{DN}} - \gamma * \frac{\Delta T^2}{I_{DN}}$$ **Equation 3**

where,

α = optical efficiency

β = coefficient of the first order

γ = coefficient of the second order

ΔT = the difference of the operating temperature and the ambient temperature

Based on the experimental data from the PTSC tests at steady state conditions, the statistical method was used to correlate the performance of the PTSC's. The selection and data treatment are as follows. First, 55 steady state data sets were selected from the 1800 collected during the 15 day tests. Second, the mean values of the experimental data were calculated based on all of single data collected per minute in each of these steady state sets. Third, the system energy balances were checked by using the calculated 55 steady state data sets. The results showed that the measurements were in reasonable agreement with the energy balances, taking into account the sensor accuracy and the impacts on energy of other devise such as the pumps. Fourth, the mean values of experimental data were introduced into the statistical tool to generate the correlation of the calculated η values by using multiple regressions.

According to the rule of thumb for multiple regressions, the size of the data sample must be at least 20 times as many cases as independent variables. In the PTSC efficiency multiple regression, there are two independent variables: $I_{DN} * \cos(\theta)$ and $(T_{in} + T_{out})/2 - T_{am}$, so 55 data sets are sufficient to determine the performance of the PTSC. The data was analyzed and performed the multiple-regression in MINITAB commercial statistics software. The optical efficiency, α, is 0.634 and the linear coefficient of thermal losses, β, is 1.4 W/^{o}C m2.

$$\eta = 0.634 - 1.4 \frac{(T_{in} + T_{out})/2 - T_{am}}{I_{DN} * \cos(\theta)}$$ **Equation 4**

In addition, multiple regression was also implemented to consider the solar collector efficiency equation in the second order form; however, the results showed considerable experimental scatter. The major reason for this scatter may be the fact that the actual thermal loss from radiation is proportional to the fourth power differences of the operation temperature and the sky temperature rather than the second power.

5 Discussion of the test program

The solar PTSC - absorption chiller based cooling and heating system has been evaluated in four types of test. The PTSC performance was determined by tests at a steady state. The simplified solar collector efficiency equation was defined in the form of a linear relation with the operation temperature of the PTSC. The optical efficiency, α, was estimated by data to be 0.64. This optical efficiency is related to the reflectance and cleanliness of the reflector, optical error, tracking error, transmittance and absorptance of glass, and the absorptance of the absorber pipe coating. The coefficient, β, in the empirical equation for the PTSC overall efficiency, Equation 2, was estimated by data to be 1.4 W/^{o}C m^{2}.

Experimental data shows that the solar thermal system normally takes about three to four hours to heat the system to 160 ^{o}C, the nominal operating temperature of the absorption chiller. The overall system has a high heat capacity. This heat capacity consumes much useful solar energy and prolongs the warm up period before solar energy is available to be used by the absorption chiller or the heat recovery exchanger. Design approaches and operational methods for reducing the heat capacity of the system and the warm up period are now being devised.

The basic performance of the installed absorption chiller has been studied. In the cooling cycle, the full rated capacity of the absorption chiller is about 12 kW with a COP of 1.0 – 1.2. Its heating capacity, however, is low, about 4 – 5 kW: and the heating efficiency is about 0.38. Solar heating using a heat recovery exchanger, rather than an absorption chiller, is recommended because it has higher solar energy gain, a shorter solar time for warm up, and a greater efficiency.

A PTSC performance model has been developed and validated that estimates temperatures in the collector, heat losses, and the overall solar conversion efficiency based on fundamental mass and energy balances and heat transfer computations programmed in the Engineering Equation Solver (EES). Also, the annual performance of the overall solar cooling and heating system for the Intelligent Workplace, the IW, has been modeled and programmed in the TRNSYS modeling system.

Additional information on the experimental data and analyses based on using the PTSC model and system simulations will be found in the Ming Qu's thesis: "Model Based Design and Performance Analysis of Solar Absorption Cooing and Heating System" to be published in February 2008.

9 November 2007