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EXPERIMENT BASED PERFORMANCE ANALYSIS OF A SOLAR ABSORPTION COOLING AND HEATING SYSTEM IN CARNEGIE MELLON UNIVERSITY

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ABSTRACT

The center for building performance and diagnostic (CBPD) at Carnegie Mellon University has successfully designed, installed and tested a solar cooling and heating system to assess the feasibility of solar cooling for small scale commercial buildings or residential buildings with aspects of technology and energy efficiency.

This solar cooling and heating system is primarily comprised of parabolic trough solar collectors, PTSC's and a 16 kW dual energy source double effect (2E) absorption chiller. The 2E absorption chiller driven by PTSCs was tested to produce chilled water or hot water throughout a number of clear days in summer and winter. The analyses of the experimental data defined the system performance: the efficiency of the solar collector, the capacity and COP of the chiller, and the heat transfer coefficient of the heat recovery exchanger, by using a statistical approach, based on the energy balance equation. In the solar cooling tests during July 2007 in Pittsburgh, PA, the average efficiency of PTSCs was 35% when they were operated at about 155˚C for driving the 2E absorption chiller and the chiller was able to provide 8 to 14 kW cooling with COP in the range 1.0 to 1.2; the overall system efficiency is in the range 0.35 to 0.41.

In the near future, this solar absorption cooling and heating test system and its operation will be integrated with the cooling, heating and ventilation units for long term utilization.

Keywords: absorption chiller, parabolic trough solar collector, center for building performance and diagnostic, solar absorption cooling and heating system

1. INTRODUCTION

In recent years, the increasing costs of energy and the increasing demand for building have caused people to seek alternative cheaper, renewable energy sources for building air conditioning. In addition, the environmental issues such as global warming, ozone depletion, and energy conservation, are another important factor impelling people to look for a space cooling without gas combustion or electricity. As one of the renewable energies, solar energy occurs approximately coincident with comfort cooling demand. The use of solar energy for building cooling can potentially provide the solution to these economic and environmental problems.

Solar absorption cooling was a significant research interest from 1970 to 1980, when a number of demonstration projects were conducted in the United State. However, these systems failed to establish a significant global market for cooling systems due to their high initial cost, a lack of commercial hot water driven absorption chillers, and the scarcity of demonstrations and impartial assessments by reputable institutions (Kulkarni 1994) especially for solar thermal driven cooling systems using double effect absorption chillers. There are few successful studies of solar thermal systems incorporating double effect (2E) absorption chillers. For instance, a demonstration solar thermal driven cooling system (Duff 2004), installed for a commercial building in Sacramento, California, has operated 106.5 m^2 Integrated CPC collectors only at 90-130C to serve a 70kW (20 ton) 2E McQuay/Sanyo chiller, which was modified from gas firing to hot water driven. The U.S. Army's Yuma Proving Ground solar system has successfully operated a 1245 m^2 of Hexel PTSC collectors to drive a 160 ton LiBr/H2O 2E absorption cooling system for nearly 14 years since its installation in 1979 (Hewett 1995). The Center for Building Performance and Diagnostics (CBPD) of Carnegie Mellon University (CMU) assesses the feasibility of solar cooling for small scale commercial buildings or residential buildings through installation and evaluation of a new system with an advanced system configuration using recently available solar and chiller equipment. The unique features of the current CMU's solar cooling and heating system are the use of a 2E double energy sources (hot water or natural gas) driven chiller with both cooling and heating function without thermal storage, and solar and load transients are controlled by use of the gas burner and defocusing the PTSCs to control heat fluid temperature.

2. SOLAR ABSOPRTION COOLING AND HEATING SYSTEM IN CARNEGIE MELLON UNIVERISTY

2.1 System overview

The solar cooling and heating system in Carnegie Mellon University has been designed to cool or heat an office space. To meet the cooling and heating load of this space, a 16 kW 2E absorption chiller was selected and installed. This chiller is driven either by hot water or by natural gas to provide cooling in the summer and heating in the winter. This chiller incorporates a cooling tower to reject heat from its operation as required in cooling cycle. To satisfy the requirement of the 2E absorption chiller, 52 m^2 linear parabolic trough solar thermal receiver arrays were installed with its circulating propylene glycol water mixture, instrumentation, circulation pumps, expansion/pressure tank, and drain/ filling apparatus. A web-based automation system, Automated Logical Co. control system (ALC), was also installed to operate the solar collector, heat exchanger and the absorption chiller with their auxiliary system, monitor the overall system status, and collect experimental data. In addition, a heat exchanger was installed parallel to the absorption chiller for comparing the system performance of a heat exchanger based solar heating with an absorption chiller based solar heating. The piping and instrumentation diagram, PI &D, of this solar cooling and heating system is indicated in Figure 1.

2.2 Parabolic trough solar collector

The solar receivers installed are four modules of single axis tracking concentrated parabolic trough solar collectors (PTSCs). Each of the modules is comprised of a parabolic trough reflector mirror, a surface treated absorber pipe at its focal line surrounded by an evacuated transparent tube, supporting structure, and a tracking mechanism. It has a 6 m by 2.3 m aperture opening. This 13.34 m^2 aperture area and 0.68 m^2 receiver area corresponds to a 19.6 concentration ratio. The reflector mirror has a 0.8 typical reflectance. The absorber pipe is coated with selective blackened nickel. This coating has high absorptivity for short length solar radiation and low emissivity for long length heat radiation. The absorber pipe is contained within an evacuated glass tube to minimize convection and radiation losses. PTSCs typically have a higher efficiency at the high temperatures than plate solar collectors such as a flat solar collector.

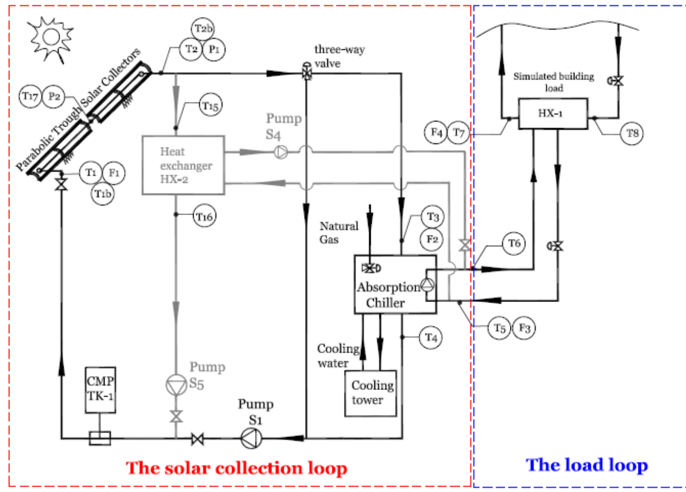

Figure 1 PI & D diagram of the test solar absorption cooling and heating system

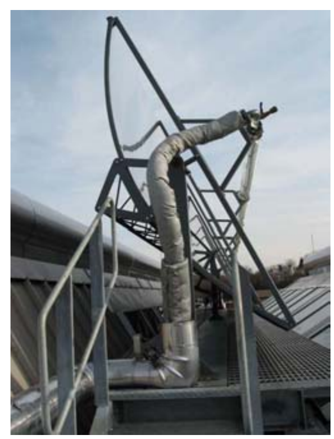

Figure 2 The parabolic trough solar collector

2.3 Double effect absorption chiller

The 2E absorption chiller could provide both chilled water and hot water by using hot water from solar field or natural gas. It uses lithium bromide as the sorbent and water as the refrigerant. In the cooling cycle, the water in Evaporator is vaporized at a low pressure, absorbing heat transferred from chilled water flow. Then the water vapor is absorbed into concentrated LiBr solution in the Absorber indicated in Figure 3. A solution pump then pumps up the dilute LiBr solution to the Regenerator that operates at a higher pressure and a higher temperature to vaporize water from the solution making use of thermal energy from the solar collectors or from the natural gas burner. The water vapor is condensed by rejecting heat to cooling water in the Condenser. Next, condensate water is passed through an expansion nozzle into the Evaporator. This condensate water is vaporized there, so the cooling cycle repeats again. A single valve shown on Figures 3 and 4 can be opened to switch the chiller from the cooling to heating mode. In the heating mode, the water vapor boiled off LiBr solution in the Regenerator, directly flows into the Evaporator, as shown in Figure 4. The evaporator now acts as a condenser and heats the second water stream for heating.

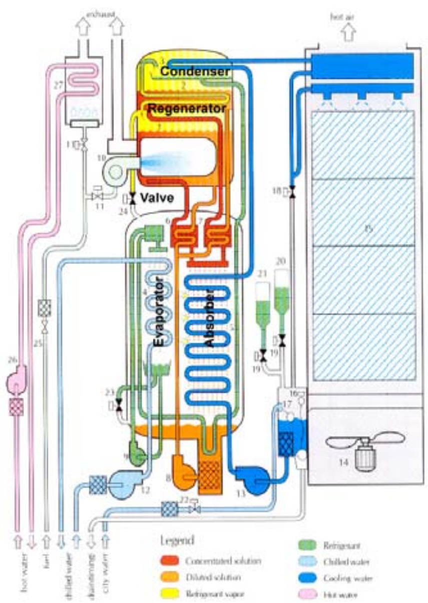

Figure 3 The 2E absorption chiller in the cooling mode[1]

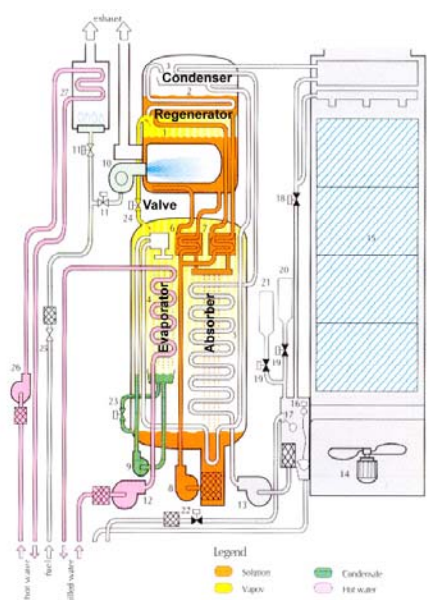

Figure 4 The 2E absorption chiller in the heating mode

[1] From the absorption chiller brochure of Broad Air Conditioning Co.

2.4 Instrumentation, control and data acquisition control system

ALC control system is a web-based, BACnet as protocol, control and data display system. It collects the measurement data from the operation of the solar collector, the absorption chiller, heat exchangers and variable load heat exchanger to evaluate the device and the system performance. This system works together with two individual control systems: the PTSCs control and the 2E absorption chiller control from manufacturer. Both of the PTSC control system and the chiller control system have their own portable control panels and communicate with each other during system operation. ALC control system controls devices other than the PTSC and the absorption chiller in the system, and also is severed as major data acquisition and data analysis system. 21 sensors installed in ALC control system include flow rate sensors, RTD temperature sensors, pressure sensors, and pyrheliometer for direct normal solar radiation. Signals from these sensors are received, converted, sent to database by ALC's controller. The ALC's web control server (WebCTRL) programs the system operation control logic, sets or changes control parameters, and displays the system operation. It also plots and presents historical data in various forms, such as graphics, trends, and reports.

3. THE TEST PROGRAM ON THE SOLAR ABSORPTION COOLIGN AND HEATING SYSTEM

3.1 Test program overview

The test program of the solar absorption cooling and heating system aims to characterize devices and systems, and evaluates the annual system performance simulation. It was planned, and conducted in clear days or mostly clear days from February to September of 2007. The experiments in the test program are classified into two groups: Solar absorption cooling / heating daily test and heat exchanger based solar heating daily test.

3.2 Solar absorption cooling / heating daily test

In the solar absorption cooling / heating daily tests, the heat transfer fluid (HTF) was circulated through by-pass until the temperature desired by the absorption chiller was reached in the morning; then the HTF was diverted through absorption chiller to produce chilled water or hot water for space cooling or heating. The amount of solar energy supply was no longer adequate to provide heat for the absorption chiller in the late afternoon; then HTF was circulated in the collection loop through by-pass again, as indicated in Figure 5.

3.3 Heat exchanger based solar heating daily test

In heat exchanger based solar heating daily 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. 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 6. Finally, when amount of solar energy supply was no longer adequate to operate HX-2 due to the heat loss of system and the reduction of the direct normal solar radiation, the system operation was halted.

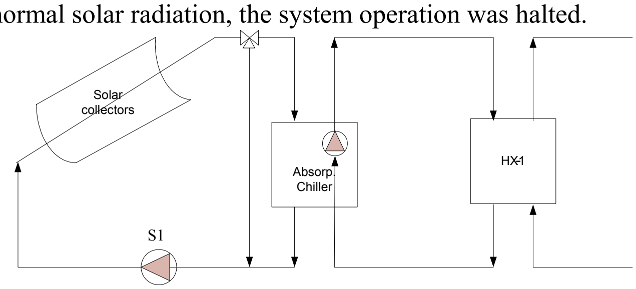

Figure 5 Schematic diagram of solar absorption cooling/heating daily test

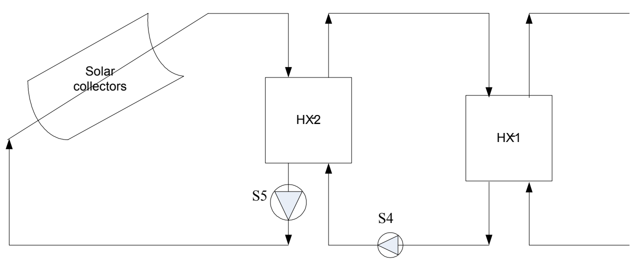

Figure 6 Schematic diagram of heat exchanger based solar heating daily test

4. TEST RESULTS AND PERFORMANCE ANALYSIS OF SOLAR COOLING AND HEATING SYSTEM

4.1 Results of solar absorption cooling daily test

Solar absorption cooling tests were performed in thirteen days from June to August 2007. It was difficult to have stable direct normal solar radiation throughout a day during this period in Pittsburgh. The operation procedures of these tests are follows:

1. Started up the PTSCs; the PTSCs automatically tracked the latitude of the sun throughout a day.
2. Started up the absorption chiller by using natural gas.
3. The HTF was heated and circulated through by-pass in the solar collection loop.
4. The chiller shut off the gas burner and the HTF was diverted through the chiller, when the HTF was reached the temperature required by the chiller.
5. If the solar energy was excess, the PTSCs were defocused to reduce solar energy collected. If the solar energy was not adequate for the chiller operated at full capacity, the chiller load was reduced by reducing flow rate of fluid at the cold side of HX-1, so that the absorption chiller could still be operated at the partial capacity by the limited solar energy.
6. When the solar energy was not enough for the chiller, the chiller turned on the gas burner to continuously provide chilled water by using natural gas. The HTF was diverted through by-pass and circulated in the solar collection loop again.
7. Shut down the PTSCs and the absorption chiller.

Figure 7 through 10 show system temperatures and heat quantities for cooling operation throughout two days in July 2007. Figure 7 and 8 are 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 throughout a day. It took about three hours or more to heat the system and the HTF from the ambient temperature to 160 ˚C, the temperature at which the absorption chiller is programmed to switch from natural gas to solar energy in the morning. The absorption chiller then had been operated for about four hours a day depending on the available solar energy. 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 in Figure 8. After 16:30, the solar collector could not provide enough energy to operate absorption chiller efficiently. The HTF in the solar collection loop then bypassed the absorption chiller, and the natural gas burner was used to drive the chiller. Figure 9 or 10 show these corresponding calculated heat quantities:

- the solar input marked as I_{DN}*Aa*cos(θ), the product of direct normal solar irradiation from pyrheliometer measurements, actual aperture surface area, and the cosine of the incident angle
- the solar energy delivered by PTSC marked as Q_solar_delivered, the product of the HTF flow and the temperature difference over the PTSCs
- the delivered thermal energy to the chiller marked as Q_chiller_solarinput, the product of the HTF flow and the temperature difference over the chiller
- the cooling capacity provided by the chiller marked as Q_chiller_cooling, the product of the chilled water flow and the temperature difference over the chiller

As indicated by these figures, 17 ~ 45 kW solar input impinged on the aperture surface of solar collector throughout a day. Corresponding to this solar input, PTSC was able to delivered 5 ~ 15 kW energy to the chiller. Solar energy delivered was larger than the energy used by chiller at the beginning of the chiller operation while the relation between them was reversed in the later afternoon. In the typical solar cooling operation, the solar efficiency of the PTSC's was approximately 33% to 37% when the HTF was operated at 150 ~ 160 ˚C; the COP of the 2E absorption chiller was in the range 1.0 to 1.2. The solar COP of the overall 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 by using solar energy during the tests. One of the reasons for this capacity, significantly lower than the chillers design capacity of 16 kW, was related to rate of heat transfer between HTF and LiBr solution. Rate of heat transfer depends on the temperature of HTF and heat transfer coefficient of area. Chiller capacity was limited by the operating temperature of HTF, which was about 150 ~ 160 ˚C. To get full chiller capacity, higher temperature of HTF is required. Another reason is the weather conditions in Pittsburgh. The direct normal solar radiation was relative low, typically about 600~900 W/m2 in the humid summer.

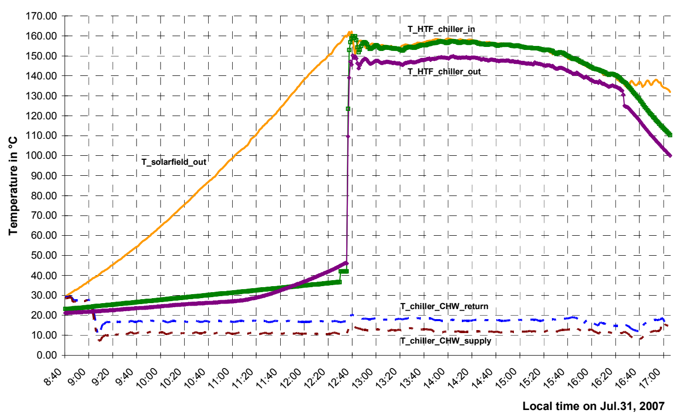

Figure 7 Operating temperature of solar cooling test on 31 July, 2007

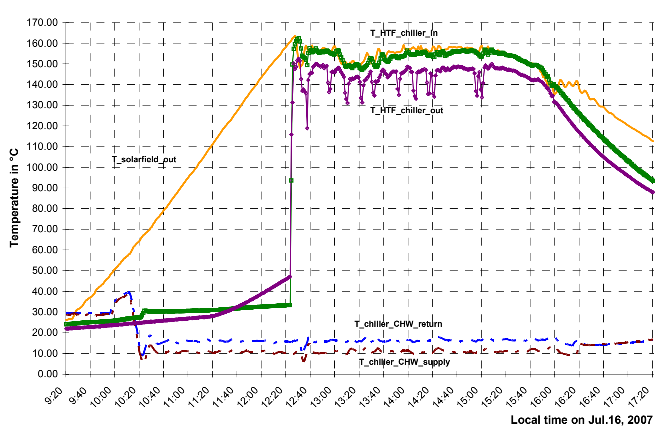

Figure 8 Operating temperature of solar cooling test on 16 July, 2007

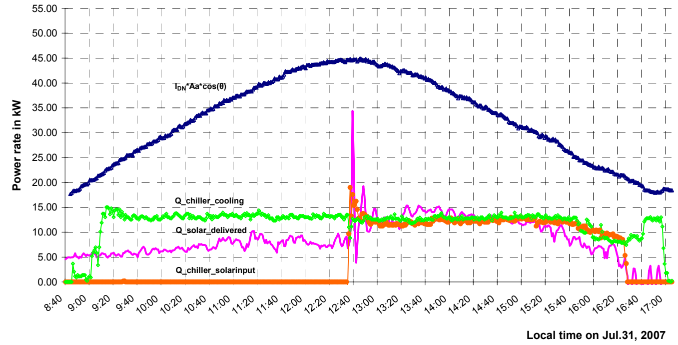

Figure 9 Cooling capacity of solar cooling system on 31 July, 2007

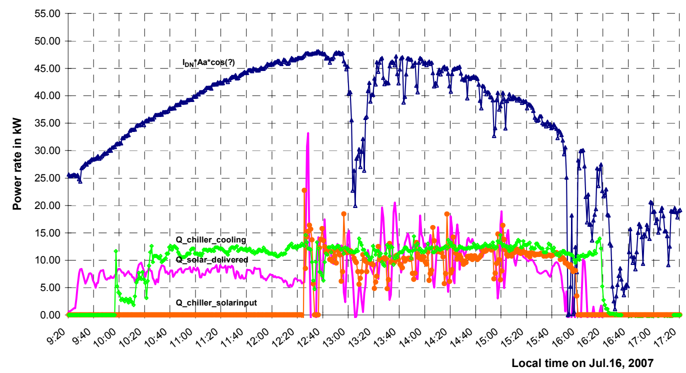

Figure 10 Cooling capacity of solar cooling system on 16 July, 2007

4.2 Results of solar absorption heating daily test

The absorption chiller based solar heating tests were carried out in cold sunny days from February to April 2007. Following the same procedure outlined for the solar absorption cooling tests, the HTF, was heated in the PTSC's, circulated through the regenerator of absorption chiller and then returned to the PTSC's. The hot water produced in the evaporator of the chiller was circulated to the load test heat exchanger, HX-1.

Similar to the curves presented above for solar cooling, Figure 11 and Figure 12 present the measured temperature and energy flow quantities of solar absorption heating test on 9 March 2007. Figure 11 indicated that there was large temperature difference, about 100 ˚C, between HTF source and hot water generated by chiller. This high temperature difference is due to the boiling point elevation of LiBr solution. The charts show that the heat delivered by the system was about 12 kW with 15 ~ 18 kW energy inputand the heating efficiency was about 0.65 ~ 0.75, when the hot water was produced by the chiller at 37 ˚C, some 20 ˚C lower than the rated supply temperature, 57 ˚C. If hot water was produced at 52 ˚C by increasing the entering temperature to 50 ˚C, the heating efficiency was significantly reduced, about 0.38. 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.

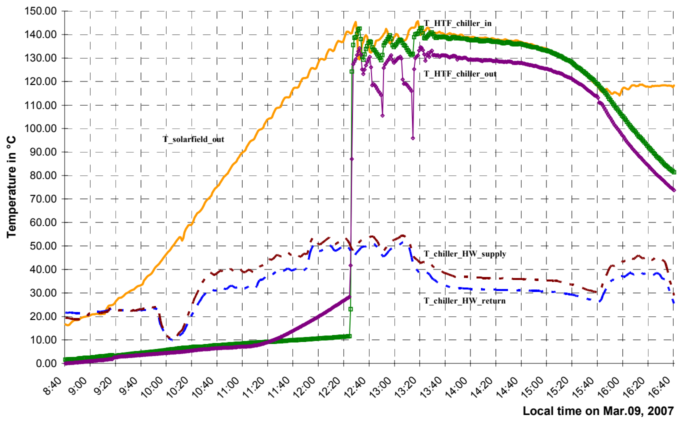

Figure 11 Operating temperature of solar absorption heating test on 09 March, 2007

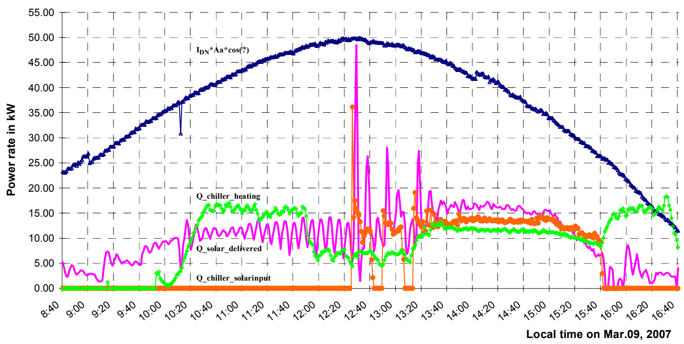

Figure 12 Heating capacity of solar absorption heating by on 09 March, 2007

4.3 Results of heat exchanger based solar heating daily test

Heat exchanger based solar heating tests were carried out in cold clear 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. The operation process was follows:

1. Started up the PTSC; the PTSC automatically tracked the latitude of the sun.
2. Heated and circulated the HTF through HX-2 in the solar collection loop without running the load loop pump.
3. When the HTF reached the temperature required by heating demands, turned on the load loop pump, so that the heat exchanger started to generate hot water for load.
4. Rejected heat from HX-2 through hot water circulated to HX-1; the flow rate of chilled water at the cold side of HX-1 was adjusted to insure the hot water generated by HX-2 balance the solar energy captured.
5. When the solar energy was not adequate for heating device's requirement, defocused the PTSC shut down the load loop pump S-4.

Figure 13 and 14 are the experimental results of heat exchanger based solar heating daily test on 2 March 2007. As shown in Figure 13, 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. The temperature difference between HTF source and hot water generated by chiller is much less, so that less heat lost during heat transfer between the HTF and LiBr solution. Figure 13 and 14 indicated that the efficiency of the PTSC was about 0.54 when the HTF was operated at 65 ~ 70 ˚C; the heat efficiency of heat exchanger was 0.9, much higher that 0.38 of absorption chiller. A comparison of an absorption chiller based solar heating and heat exchanger based solar heating according to the experimental data, presented in Table 2, shows clearly that a heat recovery exchanger based heating system is more effective. Use of the exchanger avoids the large temperature difference between the HTF and the heated water in the absorption chiller.

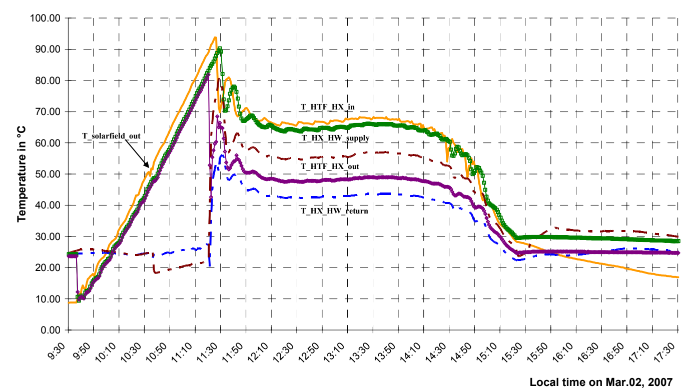

Figure 13 Operating temperature of solar heating test by heat exchanger on 02 March, 2007

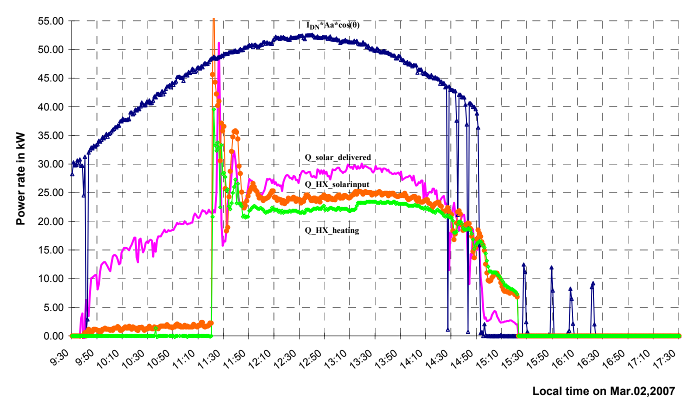

Figure 14 Heating capacity of solar heating system by heat exchanger on 02 March, 2007

	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 1 Comparison of solar heating

And it allows the collectors to be operated at a lower temperature, thus reducing heat losses from the system.

5. CONCLUSION

The PTSC performance has been determined by tests at a steady state, not included in this paper, for system analysis. The simplified solar collector efficiency equation, as shown in Equation 1, 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 0.634. This optical efficiency is related to the reflectance and cleanliness of the reflector, optical error, tracking error, transmittance and absorptivity of glass, and the absorptivity of the absorber pipe coating. The coefficient, β, was estimated by data to be 1.4 W/°C m2. This coefficient indicates the thermal properties of the PTSC.

$$\eta = 0.634 - 1.4\,\frac{(T_{in} + T_{out})/2 - T_{am}}{I_{DN} * \cos(\theta)} \qquad \text{Equation (1)}$$

The basic performance of the 2E absorption chiller installed has been studied. In the cooling mode, 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 utilization, a shorter solar time for warm up, and a greater efficiency.

Overall, this solar cooling system performance is lower than expected due to the low efficiency of PTSC when operated at high temperature and some system feature. Experimental data, for instance, showed that it took about three to four hours to heat the system to be used because of the high system 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. Therefore, the loop pipes should be designed as short and as small as possible; maintaining constant outlet temperature of solar receivers should be used to operate solar field; drain back system operation are recommended for reducing the heat capacity of the system and the warm up period.

In the near future, this solar absorption cooling and heating test system and its operation will be integrated with the cooling and heating units and the ventilation unit of the IW and incorporated with the chilled water and hot water grids of the campus.

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