FIELD TEST OF SOLAR-ASSISTED COOLING SYSTEM

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Abstract

A solar-assisted ejector cooling/heating system (SACH-2) was developed in this study. SACH-2 is designed in parallel configuration. The solar ejector cooling system is connected in parallel with an inverter-type air conditioner. In cloudy or variable weather, the performance of the ECS will always be at off-design conditions and the cooling capability of the ECS can easily be lost completely in cloudy or variable weather. A feedback tracking control system was designed for adjusting the evaporator temperature which may vary with solar radiation intensity. Field test results show that the regulation of the expansion valve is satisfactory and the ECS works properly. The A/C input power reduction can still be achieved at low solar radiation periods while the ejector is working at off-design condition. The reduction of input power of A/C is around 50% at low solar radiation periods due to the cooling performance of ECS. The field test of SACH-2 at different weathers in the present study has verified the feasibility of optimal performance control of SACH-2 to keep the ECS working at off-design double-choking condition by regulating the evaporator temperature. The feedback tracking control system is satisfactory. SACH-2 has been tested over 6 months from 2009/9/7 to 2010/3/20. The daily energy saving is 30% - 82%. The overall energy saving for the test periods is 52%.

1. Introduction

The New Energy Center at National Taiwan University has been devoted to the development of solar ejector cooling technology for a long time, especially the ejector cooling system (ECS) using low boiling point refrigerant. In the ECS, the condenser temperature must be lower than the critical condensing temperature (critical point) to obtain a high performance. Figure 1 shows the double-choking phenomenon of ECS [1,2]. Therefore, the ejector should be operated at critical mode in order to obtain a better performance. This will cause a serious problem when the ECS is applied in high ambient temperature areas such as in desert. Besides, if the ECS was driven by solar energy, it always requires a back-up system to make up the heat to keep a constant cooling capacity for space cooling during cloudy or rainy periods (Figure 2). Heat supplied by fossil fuel or electricity was generally adopted. This however causes a problem of additional investment of heaters and low efficiency in heat supply. Another problem has been noted recently that a solar heating system installed for space heating in winter seasons will produce too much heat in summer while cooling is required. ECS can thus provide a promising solution to convert the excess heat into cooling in summer.

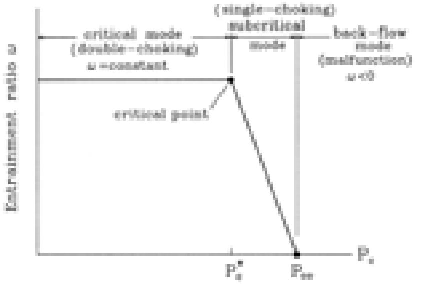

Figure 1 Double-choking phenomenon of ECS.

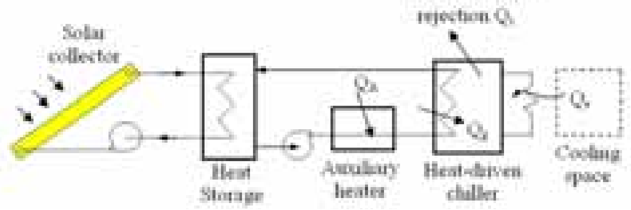

Figure 2 Conventional solar cooling system.

The present study develops a hybrid solar-assisted ejector cooling/heating systems (SACH-2) in which a conventional inverter-type air conditioner (heat pump) made of variable-speed compressor are connected in series or parallel with a solar ejector cooling system. SACH-2 is designed in parallel configuration as shown in Figure 3. The solar ejector cooling system is connected in parallel with an inverter-type air-conditioner. When solar radiation is high enough to drive ECS, the ECS will supply the cooling load and the energy consumption of the compressor can be reduced by regulating the rotational speed of the inverter-type air-conditioner. During cloudy or rainy periods or at night, SACH-2 will provide the entire cooling load from the inverter-type air-conditioner (heat pump) as usual. SACH-2 can also produce hot water by the heat pump year round to supply heat, in addition to the direct heat supply from the solar collector.

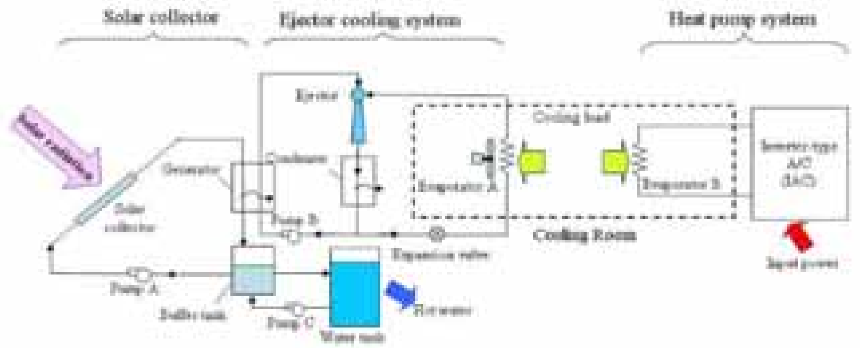

Figure 3 Solar-assisted cooling/heating system in parallel configuration (SACH-2).

Since SACH always operates under variable solar radiation, the performance of ECS will not be stable. The ejector may operate most of the time under non-critical condition which causes the ECS not to function at low solar radiation or operate at low efficiency. The development of system optimization control of SACH is thus needed.

2. Experimental setup

2.1 *System Configuration of SACH-2*

SACH-2 consists of 3 subsystems: an ejector cooling system, a solar collector system, and an inverter-type air-conditioner with variable-speed compressor. Figure 4 is the schematic diagram of SACH-2. Figure 5 is the ECS of SACH-2.

SACH-2 uses an inverter-type air-conditioner with rated cooling capacity 3.6 kW. The cooling capacity of the ECS is 1.8 kW rated at condenser temperature 38°C, generator temperature 100°C, and evaporator temperature 8°C. The overall system design specification is shown in Table 1. The ECS refrigerant is R365mfc and the nozzle design is 5.3 mm in nozzle throat diameter, 10 mm in the nozzle exit diameter, 15.5 mm in constant-area chamber diameter, and 65 degree in inlet converging angle. The ejector area ratio of constant-area section to nozzle throat is 8.55.

The ejector cooling system and the inverter-type air-conditioner operate separately. There is a microprocessor- based central control system to regulate the two systems according to the solar irradiation and solar collector system performance to reduce the power consumption of the inverter-type air-conditioner. The condenser of the ejector cooling system is cooled by a conventional water cooling tower.

Table 1 System design specification of SACH-2.

1. Inverter-type air-conditioner	
Compressor: Hitachi RAS-32JQ	
Refrigerant	R410a
Input voltage, V	AC 220
Compressor frequency, Hz	20~80
Compressor input power, kW	0.26-1.09
Cooling capacity at 54.4°C condenser / 7°C evaporator, kW	1.0-4.2
Rated COP	3.85
2. Ejector cooling system	
Refrigerant	R365mfc
Generator temperature, °C	100
Generator heat input, kW	11
Condenser capacity, kW	12.8
Condensing temperature, °C	38
Evaporator temperature, °C	8
Evaporator capacity, kW	1.8
COP_{ej}	0.16

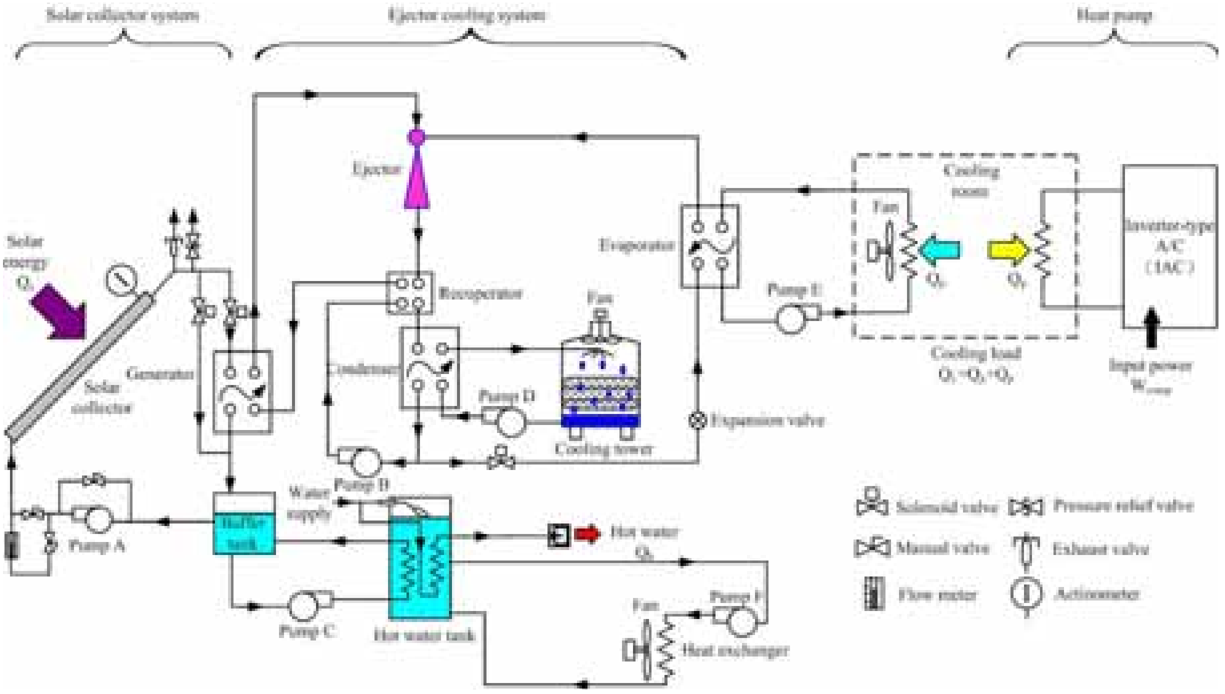

Figure 4 Schematic diagram of SACH-2.

Figure 5 ECS (1RT) of SACH-2.

2.2 *Solar Heating System*

The solar heating system (Figure 6) consists of 48 sets of vacuum-tube solar collectors with 48 m^2 total collector areas, a circulation pump, and a buffer tank to drive the generator of the ejector cooling system. The thermal efficiency of the solar collector is 0.615 at water inlet temperature 120°C. The solar energy collection efficiency is around 0.6 when the buffer tank temperature reaches 100°C for driving the ECS.

Figure 6 Solar heating system of SACH-2.

2.3 *Control system of SACH-2*

A PC-based monitoring and control system was developed in the present study for the field test of SACH-2 (Figure 7). All the data are sampled every 30 seconds.

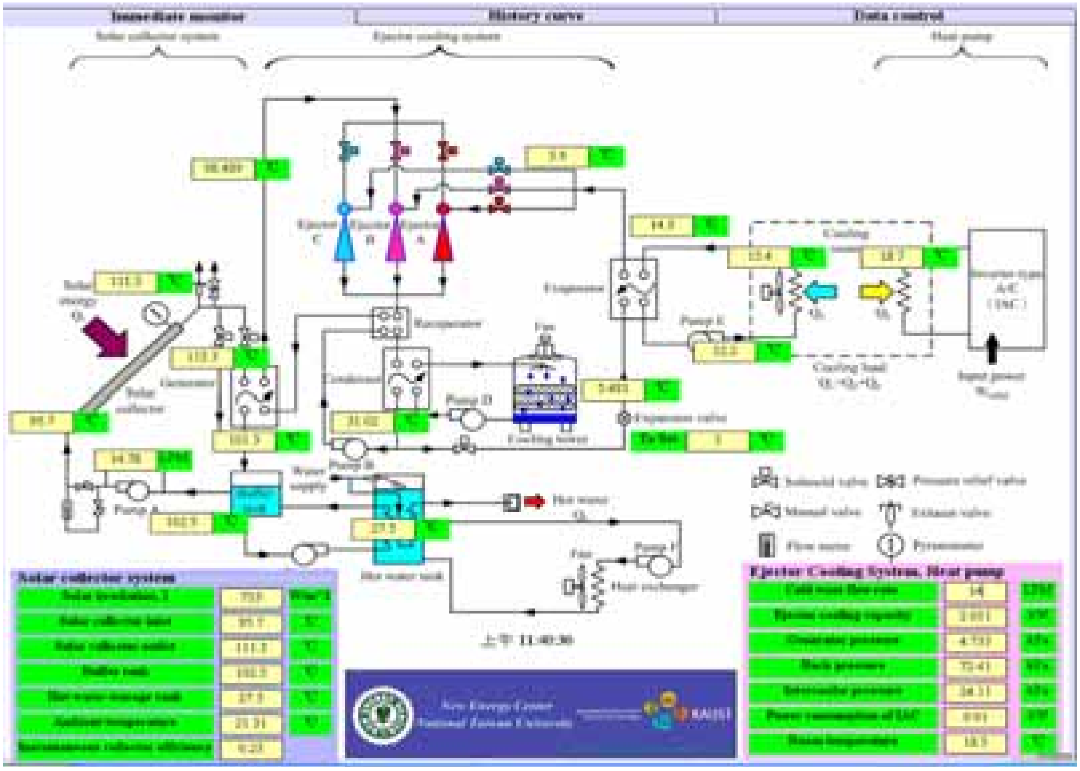

Figure 7 Monitoring system for field test of SACH-2.

In the ECS, the condensing temperature must be lower than the critical condensing temperature (critical point) such that the ejector can operate at double-choking condition. For an ejector with fixed geometry, the critical condensing temperature depends on the evaporator temperature and the generator temperature [2] which varies with solar radiation intensity. The ejector of the ECS will probably operate at off-design conditions due to the variation of solar radiation intensity, in cloudy days.

A control device using an electronic needle valve (expansion valve) was thus installed in the suction line of the ejector (at the evaporator inlet) to regulate the opening of the expansion valve to control the flow rate through the evaporator according to the evaporation temperature variation. The valve is completely closed automatically when a reverse flow will occur. The performance of an ECS operating at off-design condition can be analyzed using the performance map of the ejector [15], as shown in Figure 8.

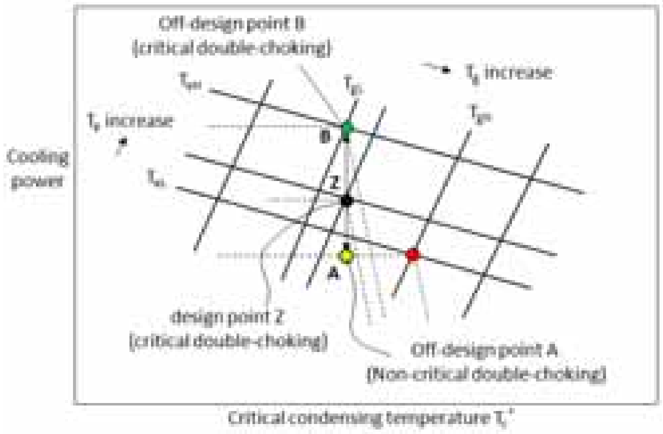

Figure 8. Performance map of ejector.

A feedback control system was designed. The tracking control is for adjusting the evaporator temperature which may vary with instantaneous solar radiation intensity. The controller of the tracking feedback control system uses the proportional control algorithm. A PC-based control system was developed to control the solar heating system, the ECS and the whole SACH-2 operation. The monitoring system (Figure 8) collects the data every 10 seconds.

3. Test Results

3.1 *Field test results of SACH-2 with optimal control*

The field test of SACH-2 with optimal control was run continuously to monitor the system performance of SACH-2, including the regulation of evaporator temperature and the performance of ECS, the power input to the air conditioner (A/C), and the power input reduction of the A/C at various operating conditions. Figure 9 shows that the cooling power from ECS varies with the solar radiation intensity. The input power of A/C is around 0.66 kW at 16PM when the ECS ceases to work. During the period 14:30PM to 15:30PM at low solar radiation intensity, the ECS still works and provide some cooling power. The input power of A/C is around 0.31 kW. The reduction of input power of A/C is around 53% due to the performance of ECS.

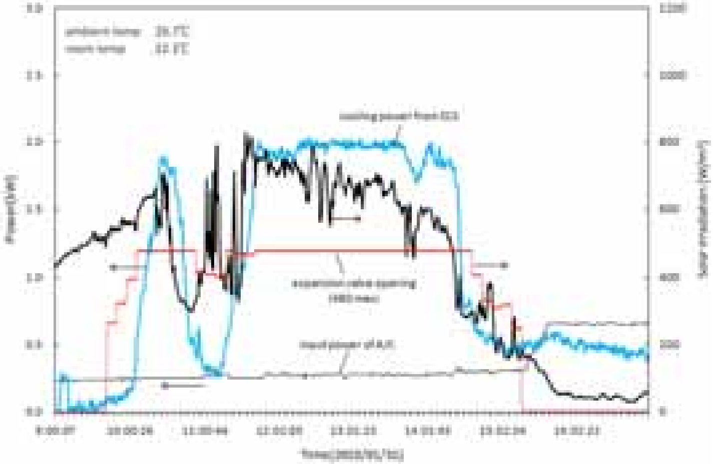

Figure 9 Performance of SACH-2 at partly cloudy day

Figure 10 shows the test results on a cloudy day with indoor-outdoor temperature difference 5.1°C (low cooling load). It is seen that the evaporator temperature setting value varies with the generator temperature. Before 11:30AM, the solar radiation is low and varies. The SACH-2 is at start-up period and the expansion valve is closed. This causes the evaporator temperature setting value at its maximum (26°C). Tracking control is not activated. After that, the tracking control system tends to track the evaporator temperature setting values. The maximum tracking error is about 10°C which happens during a sudden drop of solar radiation and generator temperature around 15:30 PM. Figure 11 shows that the cooling power from ECS varies with the solar radiation intensity. The input power of A/C is around 0.59 kW at 16:30PM when the ECS ceases to work. During the period 12:30PM to 15:00PM at moderate solar radiation intensity, the ECS works and provide some cooling power. The input power of A/C is around 0.25 kW. This means that the reduction of input power of A/C is around 57% due to the performance of ECS.

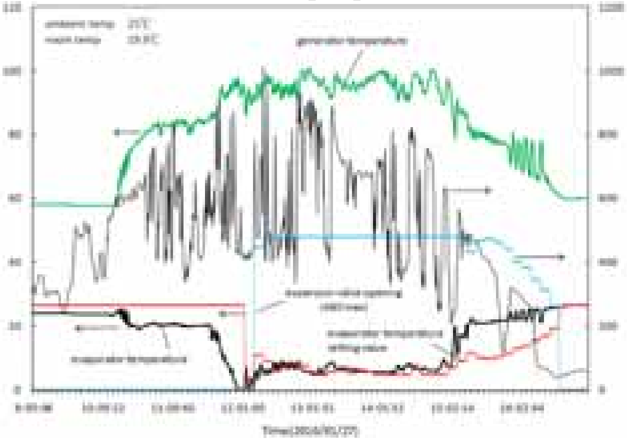

Figure 10 Performance of SACH-2 at cloudy day

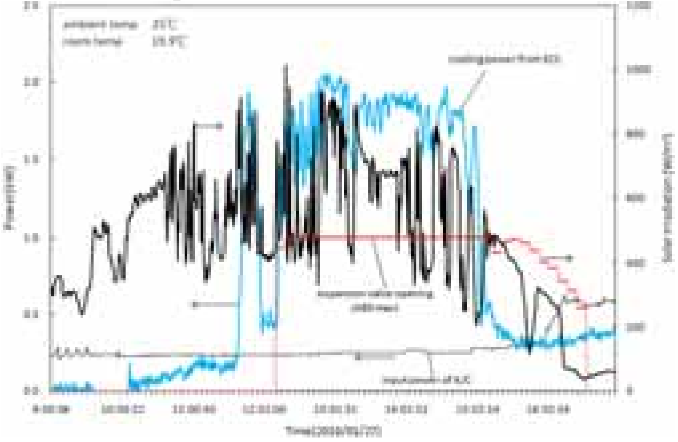

Figure 11 Performance of SACH-2 at cloudy day

SACH-2 has also been tested at hot weather. Figure 12 is the performance of SACH-2 at half-sunny day. The space cooling is in high cooling load with temperature difference (9.7°C) between the ambient (34.7°C) and the room (25°C) temperatures. The solar radiation as well as the generator temperature and the cooling power of ECS start to decrease at noon (Figure 13). The expansion valve is fully opened until the generator drops to below 80°C around 13:50PM in order to keep the ejector to perform at choking condition.

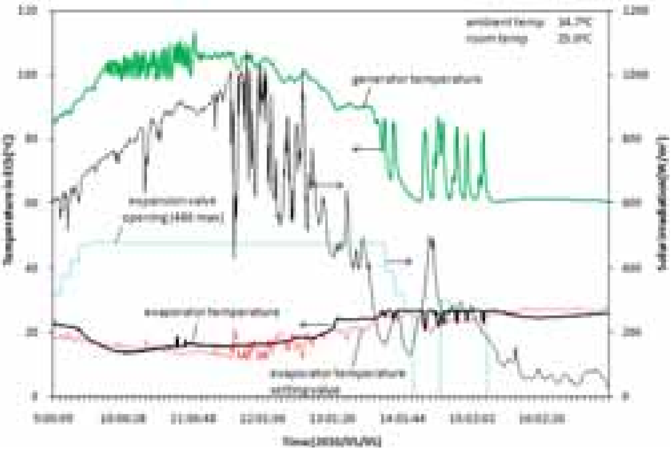

Figure 12 Performance of SACH-2 at half-sunny day.

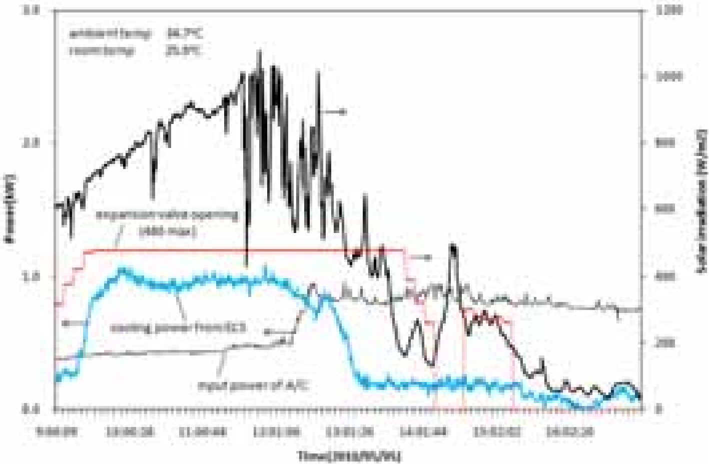

Figure 13 Performance of SACH-2 at half-sunny day.

3.2 *Long-term test results of SACH-2 with optimal control*

SACH-2 has been tested since September, 2009. Figure 14 shows the variation of daily-total ECS cooling power by solar cooling from 2009/9/7 to 2010/3/20. Figure 15 shows the daily energy saving of SACH-2. It is seen that the daily energy saving is between 30% and 82%. The overall energy saving for the test periods is 52%. Figure 16 shows that the ratio of daily energy saving varies randomly with room temperature difference (T_a-T_{room}). This is probably due to the cooling load variation with solar radiations and environment.

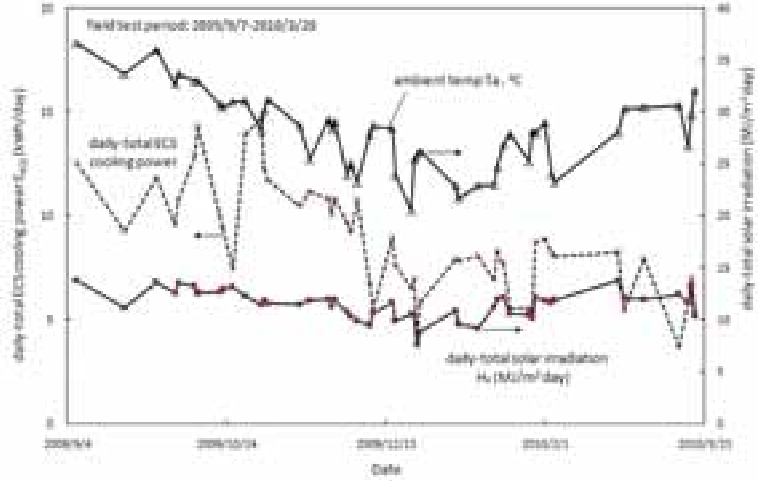

Figure 14 Long-term performance of SACH-2

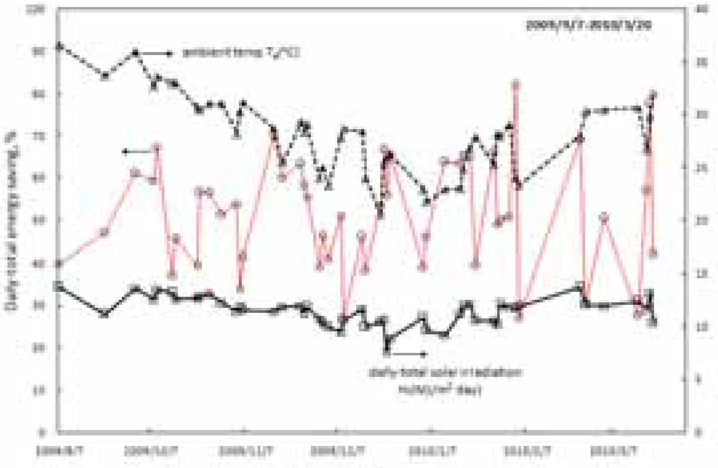

Figure 15 Long-term energy saving of SACH-2.

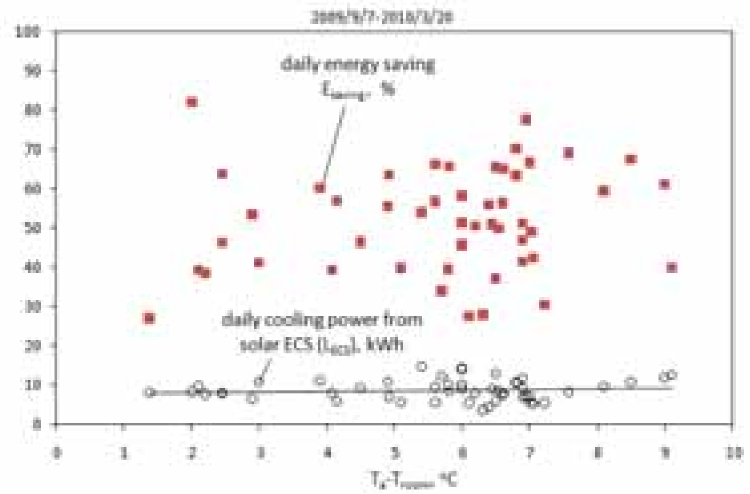

Figure 16 Daily energy saving of SACH-2.

4. Discussion and conclusion

SACH-2 is connected in parallel with an inverter-type air conditioner. When solar irradiation is high enough to drive the ECS, the cooling load is supplied by the ECS and the input power of the inverter-type A/C can be reduced by regulating the rotational speed of the compressor. During cloudy or rainy periods or at night, SACH-2 will provide the entire cooling load from the inverter-type air conditioner (heat pump) as usual.

In cloudy or variable weather, the performance of SACH-2 is rather complicated since solar radiation varies fast and unpredictable. The performance of the ECS will always be at off-design conditions and the cooling capability of the ECS can easily be lost completely in cloudy or variable weather. In order to make the ejector operate at critical or non-critical double-choking condition to obtain a better performance, an electronic expansion valve was installed in the suction line of the ejector to regulate the opening of the expansion valve to control the evaporator temperature. A feedback tracking control system was designed for adjusting the evaporator temperature $T_e(t)$ which may vary with instantaneous solar radiation intensity $I_T(t)$. Hence, a filter F is used to convert the instantaneous solar radiation intensity $I_T(t)$ into the setting value of evaporator temperature $T_{e,set}(t)$ for tracking control.

Field test results show that the regulation of the expansion valve is satisfactory and the ECS works properly and supplies cooling load. The A/C input power reduction can still be seen at low solar radiation periods while the ejector is working at off-design condition. The reduction of input power of A/C is around 50% at low solar radiation periods due to the cooling performance of ECS.

The field test of SACH-2 at different weathers in the present study has verified the feasibility of optimal performance control of SACH-2 to keep the ECS working at off-design double-choking condition by regulating the evaporator temperature. The feedback tracking control system is satisfactory although some defects still exist. The tracking error needs to be improved. This can be done by modifying the filter correlation F using more precise ejector performance map or designing a better controller to take into account the system response.

SACH-2 has been tested over 6 months from 2009/9/7 to 2010/3/20. The daily energy saving ranges from 30% to 82%. The overall energy saving for the test periods is 52%. The ratio of daily energy saving varies randomly with room temperature difference (T_a-T_{room}). This is probably due to the cooling load variation with solar radiations and environment.

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