Journal of Ambient Energy, Volume 29 Number 4, p189- 196, 2008

PERFORMANCE OF A SOLAR ASSISTED HEAT PUMP AIR-CONDITIONER, WATER HEATER AND DRYER

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Abstract

In this study, a solar assisted heat-pump system for air-conditioning, water heating and drying was designed, constructed and performance evaluated. The three applications can be served simultaneously or independently. The presence of an innovative two-phase unglazed solar evaporator-collector, where refrigerant R-134a was used as the fluid, enabled the system to operate round the clock. The evaporator-collector gained, instead of losing, a significant amount energy from the ambient due to low operating temperature of the collector. A large fraction of the energy requirements is met by a combination of energy collected from sun, ambient and the energy recovered from a vapour compression heat-pump system, which also serves as an air-conditioner. One of the two condensers served as a water heater and the other for heating the air to the required temperature for drying purposes. A series of experiment were conducted under the meteorological conditions of Singapore to evaluate the system performance under different applications and operating conditions. Maximum COP achieved during the experiment was about 6.8. This system could ensure a long-term operation under different working conditions and reduce a lot of building thermal cost, especially for hotel and hospital in the tropics.

Keywords: solar, heat-pump, air-conditioning, water heating, drying

Introduction

Due to a rapid increase in petroleum and gas prices, alternate energy sources, such as solar energy are receiving greater attention to save the consumption of oil or electrical energy resources. Solar energy is clean and inexhaustible of all known energy resources. The combination of solar energy and heat pump system can bring about various thermal applications for domestic and industrial use, such as water heating, solar drying, space cooling, space heating and refrigeration.

The concept of direct expansion solar-assisted heat pump (DX-SAHP) was first proposed in an experimental study by Sporn and Ambrose[1]. Based on these studies, Chaturvedi et al.[2] performed an investigation on the steady state thermal performance of a direct expansion solar-assisted heat pump and indicated that this system offers significant advantage in terms of superior thermal performance.

The combination of solar energy and heat pump system can support various thermal applications. Hawlader et al.[3] used refrigerant 134a in the heat pump for water heating application and the evaporator was used as a solar collector leading to a significant improvement in system COP. Hawlader et al.[4] also developed a solar-assisted heat-pump dryer and water heater. The maximum COP of the system was about 7.0.

In Singapore, more than half of the building energy consumption is attributed to ~~from~~ air conditioning urban households, especially for those buildings running air-conditioner all the day ~~time~~, such as hotel and hospital. The vapor compression air conditioning system throws the heat from a heat source (air-con room) to the ambient air without making an effort to recover it.

In this study, an attempt is made to develop a solar-assisted assisted heat-pump system to recover the condenser heat and utilized them in water heating and drying with additional heat sources, such as solar energy and ambient energy. A proto-type of the system has been fabricated and installed at the National University of Singapore. A series of experiment were conducted under the meteorological conditions of Singapore to evaluate the system performance under different applications and operating conditions.

2. System description and experiments

2.1 System description

A solar assisted heat pump system for air-conditioning, water heating and drying is shown in Fig. 1. This system consist of five major components, namely solar collector, evaporator, condenser (water cooled condenser and air cooled condenser), expansion valve and compressor. Refrigerant R-134a was used as working fluid due to the environmental and thermodynamic ~~properties~~ consideration.[5]. In the present study, two evaporators ~~that~~ connected in parallel can increase the system coefficient of performance (COP) significantly. One of the evaporators performs as solar collector which absorbs heat from solar radiation and ambient air; another evaporator absorbs heat from a room for cooling purposes. The energy from these two heat sources, plus the electrical energy supplied to the compressor, is used for water heating and air heating for drying purposes.

The superheated refrigerant vapor leaving the compressor enters the water-cooled condenser and performs water heating. The refrigerant, a mixture of vapor and liquid, leaves the water-cooled condenser and enters into an air-cooled condenser to ensure complete condensation of the refrigerant vapor. The hot air obtained from the air condenser is used for cloth drying purposes. Once complete condensation of the refrigerant vapor has taken place, the refrigerant path splits into two: one goes to evaporator-collector to absorb solar energy and the other goes to air-conditioned space to absorb thermal energy from the room to provide cooling. Superheated refrigerant vapor from the two evaporators mix together and enters into the compressor for next cycle.

2.2 System components

Two evaporator-collectors with the area of 1.5 m^2 each, made by 1mm copper plate, were connected in series, as shown in Fig. 2. A copper tube of 9.52 mm diameter was soldered at the back of each absorber plate in serpentine form (Fig. 2a). Adequate insulations were provided at the back of the collector but no glass cover was used on the top surface i.e.

unglazed collector (Fig. 2b). The collector surface was coated with a black paint with absorptivity of 90%. There is a bypass line from the exit of the first evaporator-collector to the exit of second evaporator-collector, which remains closed or open depending on the solar irradiation.

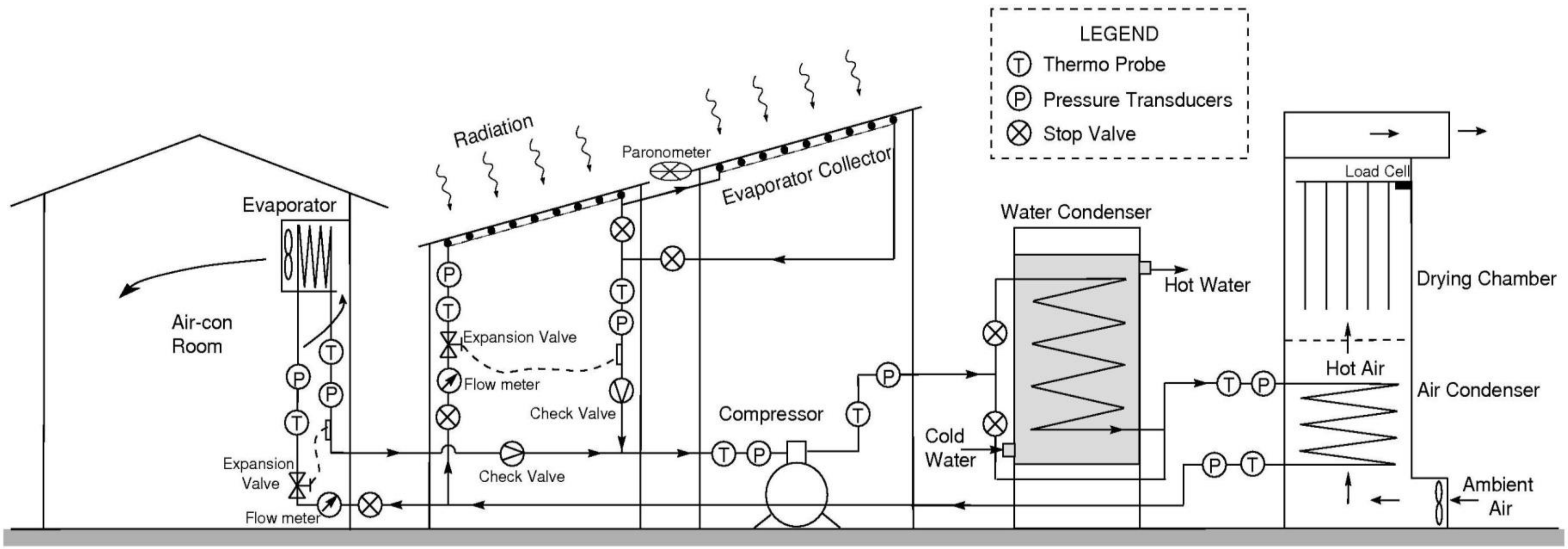
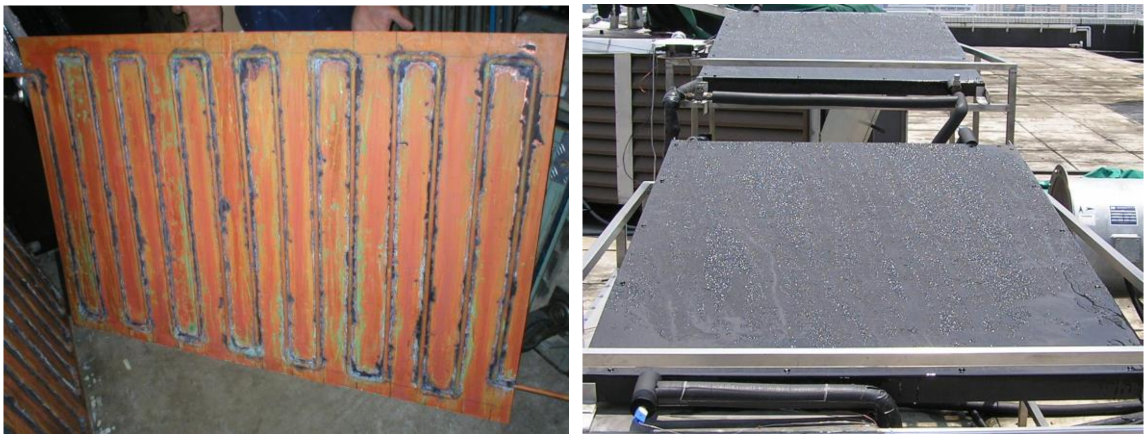


Fig. 1. Schematic overview of solar assisted heat pump air-conditioner, water heater and dryer.



(a) (b)

Fig 2. Photograph of the un-glazed solar evaporator-collector

A thermostatic expansion valve is used for the system, which maintains constant superheat at the inlet of the compressor by regulating the mass flow rate of refrigerant with the help of a feeler bulb. Actually, the feeler bulb is a remote bulb of the thermostatic expansion device that controls the degree of superheat by controlling the pressure.

An open type-reciprocating compressor is used for the system, which is directly coupled to a three-phase 3.5 kW motor. A frequency inverter is utilized to vary the compressor speed to have proper matching between the evaporator load (cooling requirement) and condenser load (heating requirement) leading to an improved efficiency. Different motor speeds under different operating conditions provide different refrigerant mass flow rate in the evaporator-collector.

The water cooled condenser also serve as water tank for hot water storage. It consists of copper coil in spiral fashion immersed in a tank filled with water. The maximum volume of the water tank is 360 liters (dimension:1.2m x 0.6m x 0.6m.) To prevent the heat losses, the condenser was properly insulated and covered with polyurethane. A bypass arrangement is designed for this water-cooled condenser to study the performance without water heating function.

A air-cool condenser integrated drying chamber is shown in Fig. 3. The refrigerant leaving the water-cooled condenser is further condensed by the air-cooled condenser. This arrangement not only recovers more condensing heat but also ensures the completion of condensation. Air flows over the finned exterior and heat transfer occur between air and refrigerant. After being heated, the air is used for drying towels. Humid air is then vented out to the atmosphere after passing through the dryer.

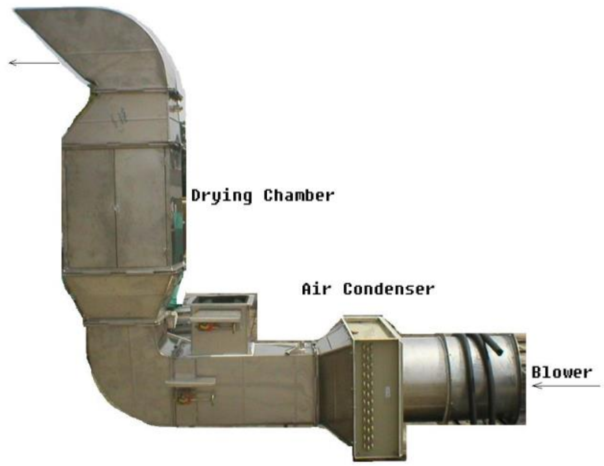


Fig.3. Construction of the air-cool condenser integrated drying chamber

2.3 Instrumentations

A well-equipped instrumentation system is deployed to measure different parameters of the system, such as temperature, pressure, and drying load.

For the measurement of temperature at different locations of the air path, T-type thermocouples are used. A pyranometer is mounted near the evaporator-collector to measure the instantaneous solar radiation. An anemometer was used for the measurement of wind speed and dry and wet bulb thermometers were used to measure ambient temperature and relative humidity. The moisture measurement for the drying of clothes is performed with the help of a precision compression load-cell. The pressure and temperature at different locations of the refrigerant path were measured using pressure transducers and thermocouple probes, respectively. The flow rates of refrigerant through evaporators were measured with the help of two magnetic flow-meters. The power consumption of the system is measured by a wattmeter.

All the above data were recorded using a data acquisition system comprising two data-loggers of 20 channels each.

2.4 Experiments

The three applications of the system can be served simultaneously or independently. Therefore, the system can be operated in different combinations of three functions by setting the bypasses of the system, as shown in Fig. 1.

In general, it can offer four fundamental operating modes, i.e. air-conditioning, water heating and drying mode; air-conditioning and drying mode; water heating and drying mode; drying-only mode. In the first two modes, the solar collector can be bypassed.

3. Results and discussion

3.1 Meteorological condition in Singapore

Results were obtained for both simulation and experimental data. Meteorological data for a typical day in Singapore is shown in Figures 4.1 and 4.2. Singapore is located at latitude 1°22'N and longitude 103°55'. There is hardly any seasonal variation of the meteorological conditions in Singapore. The typical daily variations are shown in Figures 4.1 and 4.2. Annual average ambient temperature is about 26°C.

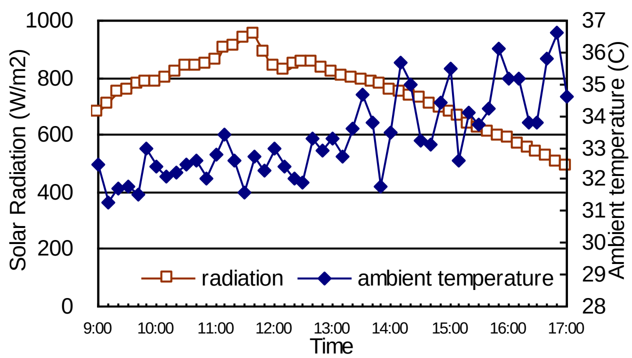


Figure 4.1 Variation of solar radiation and ambient temperature with time

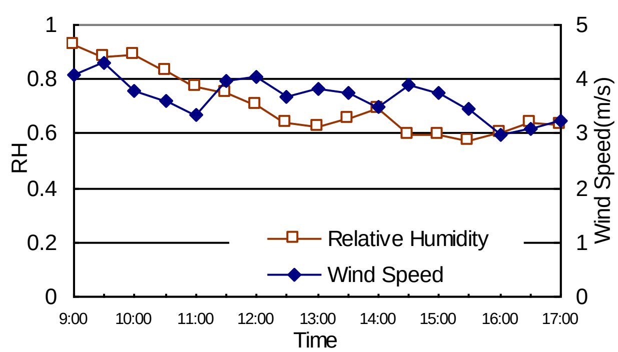


Figure 4.2: Variation of relative humidity and wind speed with time

3.2 Solar evaporator-collector performance

In Fig. 5, predicted useful energy gain (Q_u) by collector is plotted against time. Useful energy gain (Q_u) is a combination of energy gain from irradiation and the ambient. While the energy gain from the ambient, $Q_{surrond}$ is affected by ambient temperature, wind sped and relative humidity. It shows that predicted Q_u has a reasonably good agreement with experimental values. As seen from Figure 5, Q_u shows a slightly declining trend with the reduction of irradiation.

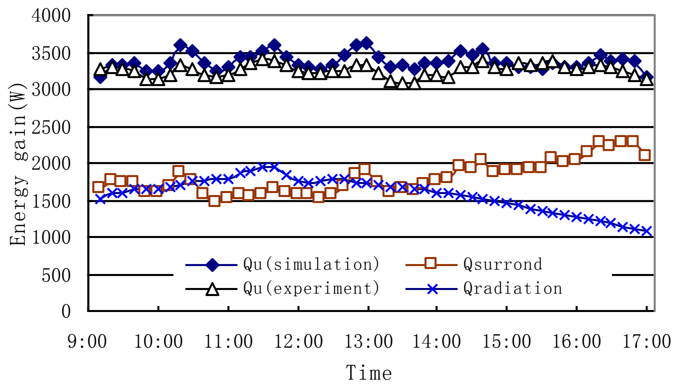


Figure 5 Variation of useful energy gain of the evaporator-collector

For high irradiation level, the unglazed solar evaporator-collector absorbed almost equivalent energy from both irradiation and the ambient. However, it absorbed much more energy from the ambient than that from irradiation when the level of radiation is lower than 600W/m^2, as shown in Figures 4.1 and 5. This property enables the unglazed evaporator-collector to supply sufficient energy even on ~~at~~ cloudy days and also at night.

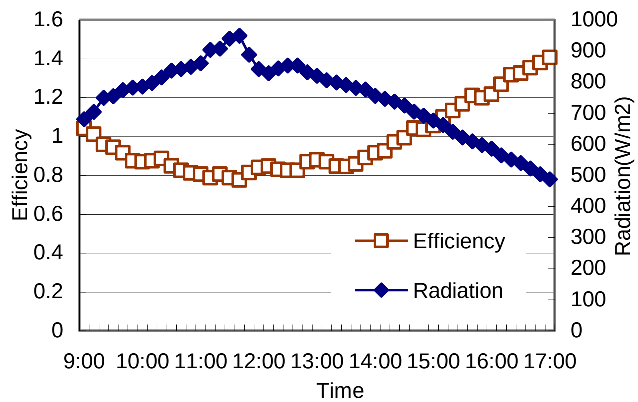


Figure 5 Variation of solar collector efficiency and solar radiation with time

Solar collector efficiency is defined as the ratio of the useful energy gain to the total incident solar radiation. As shown in Figure 5, the total useful energy gain is relatively constant when radiation is fluctuating. This feature of unglazed solar evaporator collector makes the collector efficiency to decline when radiation increases. However, due to the energy gain from ambient, the collector efficiency can be more than 1 at the condition of low level of radiation

3.3 System performance

Figure 6 shows the COP of the heat pump system in 24 hours all over the day. COP is defined by the following equation:

$$COP = \frac{Thermal\ Energy\ released\ by\ the\ condensers}{Energy\ input\ to\ compressor}$$

From the figure, it can be seen that the COP varies with time. This can be attributed to the replenishment of the hot water with cold water and resulting increased temperature lift between the evaporators and condensers.

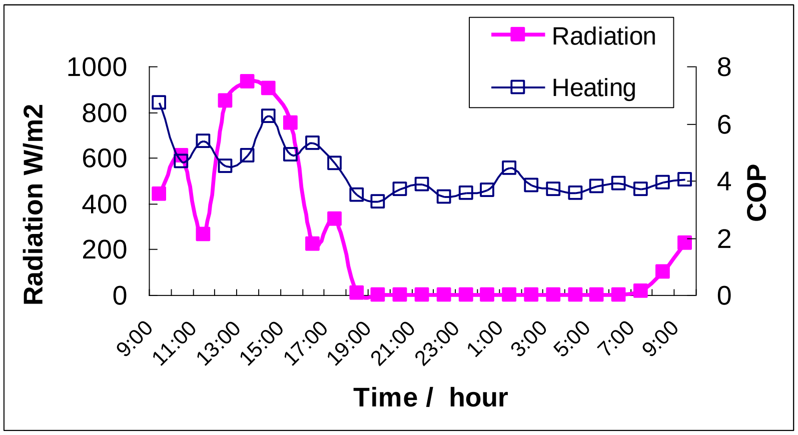


Figure 6: Variation of COP and Radiation with time

A maximum COP of 6.2 is obtained. Moreover, as seen from the figure, the maximum COP corresponds to the peak in solar radiation. This is expected as the useful energy available at the evaporator-collector is high due to the high solar radiation. The COP is maintain at around 4 over the night in the absence of solar radiation.

3.4 Air-conditioning, water heating and drying effect

For air-conditioning, the cooling load calculation shows that 3.2 kW of heat is required to be removed from the room to maintain the room temperature at 24^{o}C in the experiments. At the beginning of cooling period, the maximum cooling capacity, which can be provided by the evaporator in the room, is 10.3kW. It makes it possible for this system to bring down the room temperature from31^{o}C to 24^{o}C in just 5 minutes.

Fig.7 shows the change in refrigerant temperature at inlet and outlet of water-cooled condenser and water temperature in the tank with time. The temperature of the 400 liters of water in the tank increases in a steady manner and reaches about 60 ^{o}C in nearly two and half hours on an average day.

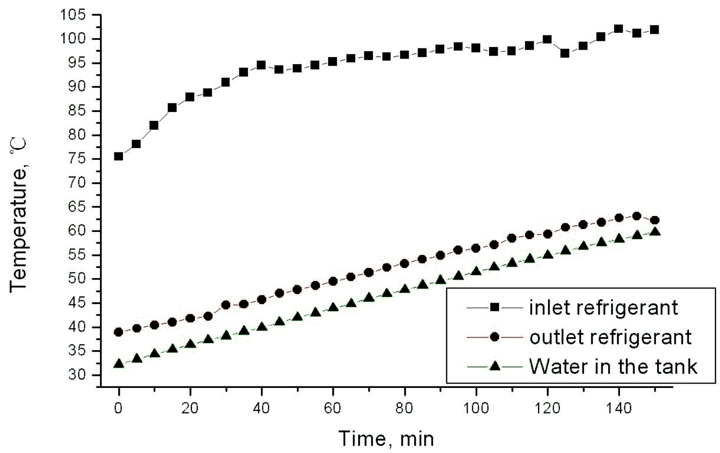


Figure 7. Variation of water and refrigerant temperatures in water tank with time

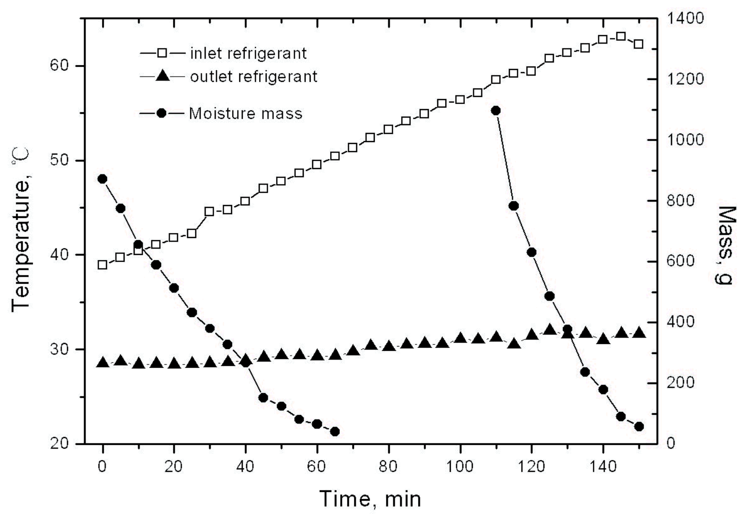


Figure 8. Variation of temperatures and moisture mass in clothes drying with time

The drying effect is shown in Fig.8, during the initial period, for lower water temperature in the tank, the drying effect is less. This is due to the fact that significant amount of heat is utilized for heating the water in the tank. As the time progresses, most of the refrigerant heat is used for heating the drying air due to the higher refrigerant temperature at the air-cooled condenser inlet. The higher refrigerant temperature is as a result of less heat transfer at the water cooled condenser due to higher water temperature.

4. Conclusions

A solar assisted heat-pump system developed for air-conditioning, water heating and drying can perform the three functions simultaneously or independently. Instead of releasing air con waste heat to the environment, it is used in combination with solar and ambient energy for water heating and drying purposes.

Experimental results show coefficient of performance (COP) of about 6.0. The two-phase unglazed solar evaporator-collector can absorb not only solar radiation but also the ambient energy. The system is considered environment friendly and show good potential for application in hotels and hospitals, where demands for cooling and hot water are considered significant.

Reference

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