A MULTI-FUNCTION SOLAR HEAT PUMP SYSTEM

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ABSTRACT

An innovative multi-function solar heat pump system is investigated in this study. The most important feature of this system is that it can serve space heating/cooling, water heating and drying simultaneously or independently. A system was designed and fabricated and a series of experiments were conducted to evaluate the performance under the meteorological condition of Singapore. Comparison of the multi-function system for different running modes and speeds of the compressor was carried out. The presence of evaporator-collector enabled the system to work round the clock, even in the absence of sunlight. Refrigerant R134a was selected as the working fluid due to its favourable thermodynamic properties. Experimental results show coefficient of performance (COP) of 4.58. Experimental results obtained under part load show that the air-conditioning greatly enhanced the heating effect. The efficiency of the unglazed evaporator-collector, which was found to be close to 1 with a maximum of 1.7, is much higher than the conventional collector. Results indicate that this multi-function system can meet domestic and industrial requirements and save considerable amount of energy when compared with the conventional air-conditioner, water heater and dryer. The system is considered environment friendly and show good potential for application in tropical areas, where solar energy is abundantly available.

Key Words: ***solar heat-pump, water heating, air-conditioning, drying.***

1 INTRODUCTION

Solar energy is clean and most inexhaustible of all known energy sources. The low temperature thermal requirement of a heat pump makes it an excellent match for the use of solar energy. The combination of solar energy and heat pump system can bring various thermal applications for domestic and industrial use, such as water heating, solar drying, space cooling, space heating, and refrigeration. Unlike thermosyphon solar water heaters, solar heat pump systems provide a real capability of upgrading low-grade energy sources from the surroundings as well as using solar energy (Hawlader et al. 2001; Lu et al. 2002). Hawlader et al. (2001) 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 COP. Lu et al. (2002) used R-22 as the working fluid under the meteorological condition of Australia. They also simulated and compared the performance of air-source heat pump and solar heat pump in eight cities of Australia. Huang and Lee (2003) also developed a heat pump solar water heater. Gillett (1978) studied the performance of a solar heat pump system for space heating under the meteorological condition of United Kingdom. Kamil (1995) conducted a simulation and experimental study for a solar and air-source heat-pump system for space heating applications under the under the meteorological condition of Turkey. Maximum COP of 4.0 was obtained in this study. Hawlader et al. (2003) developed a solar-assisted heat-pump dryer and water heater. The COP of the system was about 5.0.

The usage of solar energy depends to a great extent on the meteorological condition of the site. Singapore is located in the equatorial region, where radiation is available in abundance and stable all over the year. Most of the previous studies on solar heat pump were devoted to a single function. Thus, the applications and efficiency are limited. In this study, an attempt has been made to develop an innovative multi-function solar heat pump system for space heating/cooling, water heating and drying simultaneously or independently.

2 EXPERIMENTS

The solar assisted heat pump system considered in this study is based on a vapor compression refrigeration cycle, as shown in Fig. 1. Refrigerant R134a is used as working fluid due to the environmental and thermodynamic performance considerations (Karagoz et al., 2004). The main system components are: evaporators, compressor, water tank, drying chamber and expansion valves. The two evaporators are connected in parallel in order to improve the system performance. One of the evaporators acts as an evaporator-collector, which collects solar energy and vaporizes the refrigerant flowing through it. The second evaporator performs as an air-conditioner to cool room air.

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 has taken place, the refrigerant path splits into two: one goes to evaporator-collector and the other goes to air-conditioned space, to absorb solar energy and thermal energy inside the room, respectively. Superheated refrigerant vapor from the two evaporators mix together and enters into the compressor. Thermostatic type expansion valves are used in the present work to regulate the refrigerant mass flow rate.

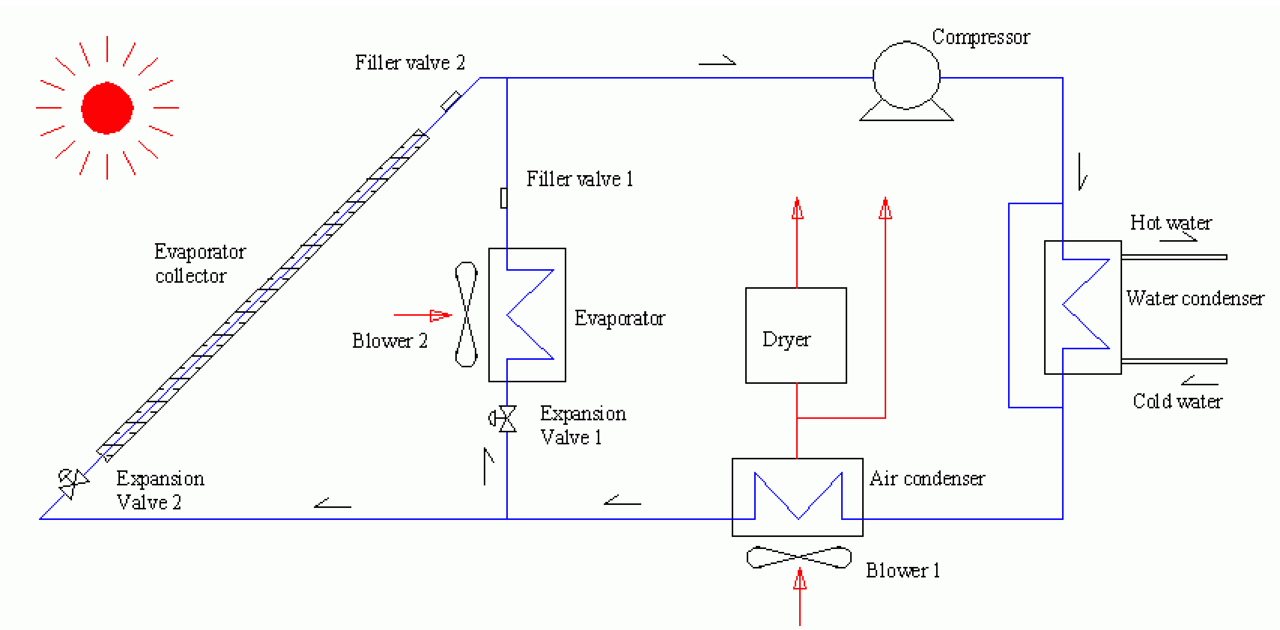

Fig 1. Schematic diagram of three-in-one solar heat-pump system

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. 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 are measured using pressure transducers and thermocouple probes, respectively. The flow rates of refrigerant through evaporators are 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.

A series of experiment were conducted to evaluate the system performance. The performance indices considered for discussion are: Coefficient of Performance (COP), Specific Moisture Extraction Rate (SMER), and Solar Collector Efficiency.

COP is defined by the following equation:

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

The SMER is defined as the ratio of the moisture removed in kg to the energy input in kWh.

$$SMER = \frac{moisture\ removed\ in\ kg}{energy\ input\ in\ kWh}$$

Solar collector efficiency is defined as the ratio of the useful thermal energy to the total incident solar radiation averaged over the same time interval. Mathematically, the efficiency of a collector is expressed as:

$$\eta_c = \frac{\int_{t_1}^{t_2} Q_u\, dt}{A_c \int_{t_1}^{t_2} I_T\, dt}$$

The experiments were conducted under various combinations and include the following:

- Performance under full-load condition: when air-conditioning, water heating and drying are used.
- Only water heater and air-conditioning are used, blower for the dryer is switched off. Only water condenser to complete the condensation.
- When only water heater and dryer are used, refrigerant path through air-con evaporator will be switched off.
- When only air-conditioning and dryer are used, water condenser is bypassed.

3 RESULTS AND DISCUSSION

3.1 Metrological Condition

The meteorological data for a typical day in Singapore is presented. Figure 2 shows the variation of solar radiation and ambient temperature with time for a typical day.

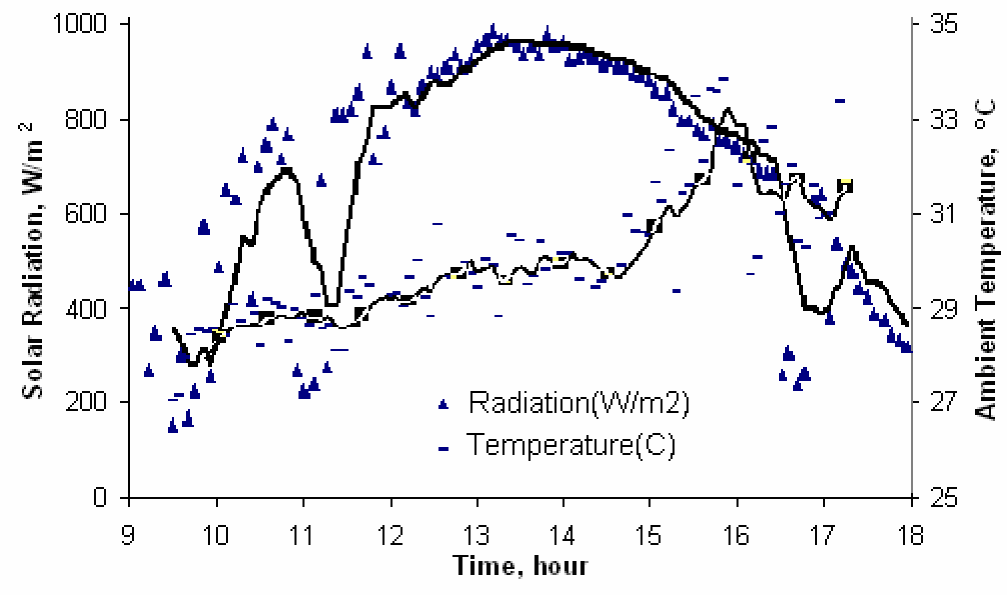

Fig. 2. Variation of solar radiation and ambient temperature with time for a typical day in Singapore

3.2 Solar Collector Efficiency

Variation of evaporator-collector efficiency and solar radiation with time is shown in Fig. 3. As seen from the figure, evaporator-collector efficiency ranges from 0.6 to 1.7. The evaporator-collector efficiency of one or more than one can be attributed to the fact that the collector absorbs energy from ambient as well. Because of the influence of this energy absorbed from ambient, instead of heat losses from the collector, the collector efficiency remains fairly high even with the change in solar radiation, as seen from the Fig. 3.

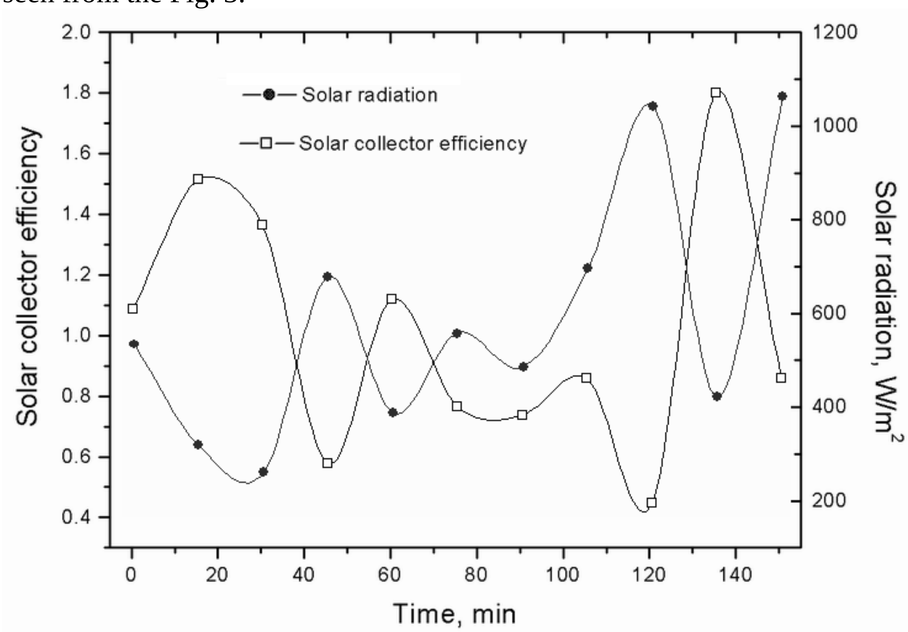

Fig. 3. Variation of solar collector efficiency and irradiation with time.

3.3 Performance Under Full-Load

3.3.1 Air-conditioning:

Figure 4 shows the change in room and refrigerant inlet and outlet temperature with time. As seen from the figure, the room temperature stabilizes with time. The ambient temperature remains fairly constant although the radiation fluctuates with time.

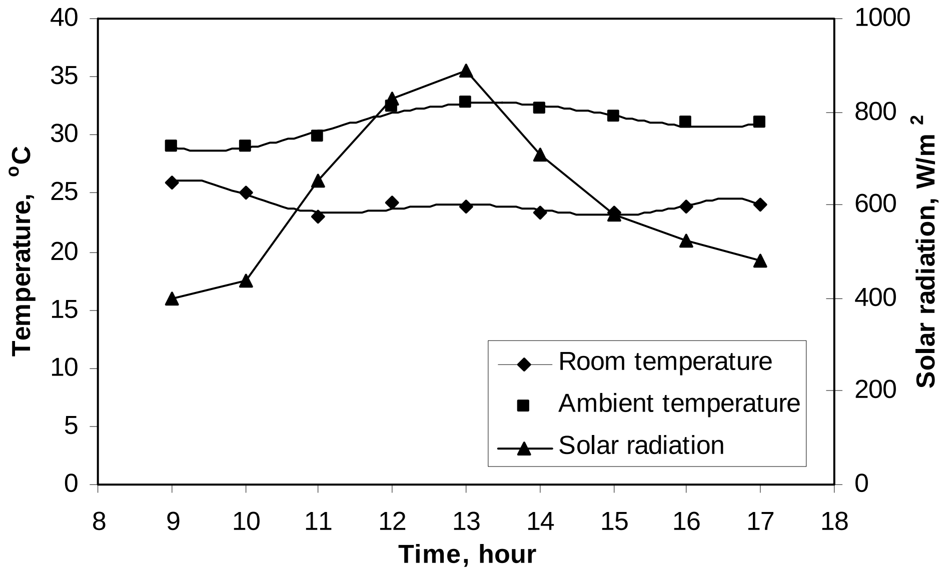

Fig. 4. Variation of temperature of air-conditioned room with time.

For air-conditioning, the cooling load calculation shows that 3.2kW of heat is required to be removed from the room. In the experiments, the room temperature was maintained at 24C.

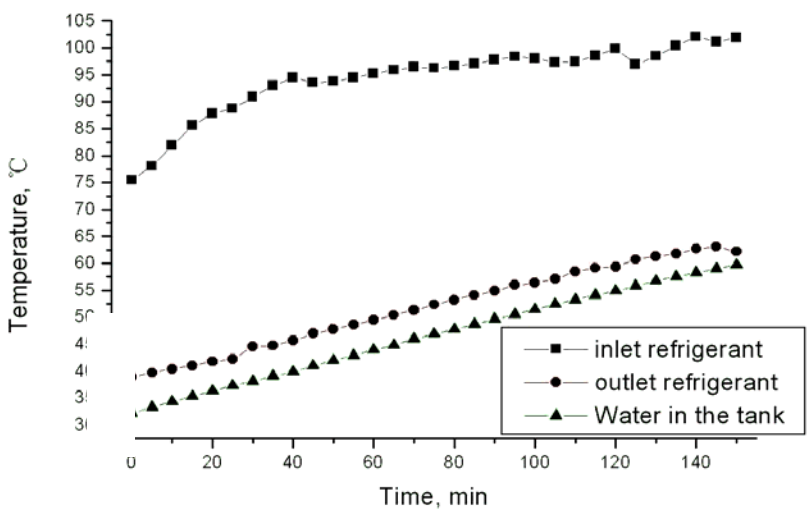

Fig. 5. Variation of water and refrigerant temperature with time

3.3.2 Water Heating:

As shown in Fig. 5, the temperature of the 400 liters of water in the tank increased in a steady manner and reached about 60 °C in nearly two hours. The hot water was drawn from the water tank to meet the load requirements. As seen from the figure, the water in the tank reached the maximum temperature of 60 °C and then stabilizes. This is attributed to the fact that heat transfer between water and refrigerant declines due to high water temperature. The withdrawal of hot water from the tank at regular interval improves the performance.

3.3.3 Drying

Figure 6 shows the comparison of experimental moisture content of clothes with time at different drying temperature. For the same air flow rate, it is clear from this figure that the drying rate increased with increasing drying air temperature. For a temperature of 45 ^{o}C, the drying of clothes was completed within 20 minutes.

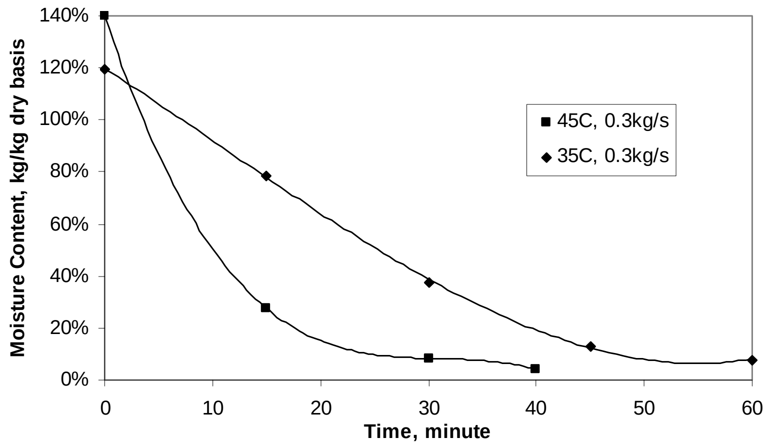

Fig. 6. Variation of measured moisture content with time for different drying temperature.

A maximum of SMER value of 0.613 kg/kWh was observed for these experiments.

3.3.4 Coefficient of Performance (COP)

Figure 7 shows the variation of COP with time when compressor speed is 1200rpm. As seen from the figure, the higher COP values lie in the higher solar irradiation region, indicating that the COP increases with increase in solar irradiation. This is expected, as the solar irradiation increases the collector evaporator operating temperature resulting in lower temperature lift between the evaporator and condenser. A maximum COP of 4.58 was observed.

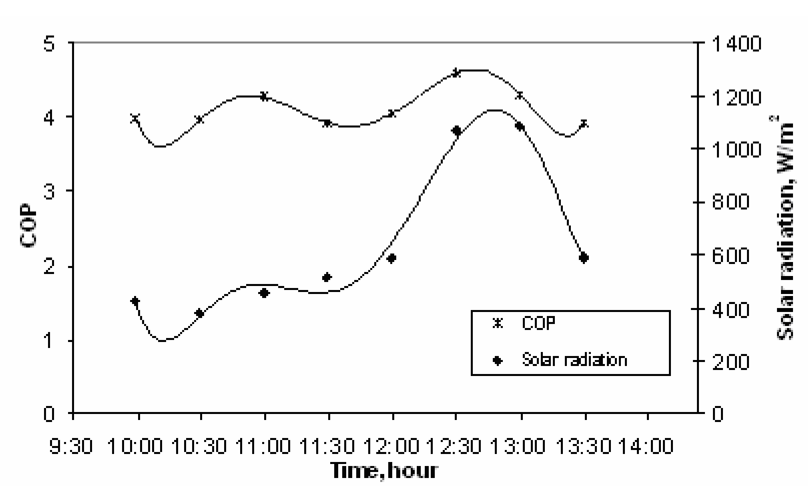

Fig. 7. Variation of COP with time (full mode)

3.4 Performance of Different Combinations

This system can serve the three functions simultaneously or independently.

- When the blower at the dryer is shut off, water heating and air-conditioning performance is not affected much.
- When air-conditioning is switched off, all the refrigerant will go through the evaporator-collector and
- the heat energy from the system is reduced substantially. Water heating rate is reduced by 50 to 60%.
- Clothes drying rate is reduced 60% to 80%.
- When water condenser is bypassed, air condenser alone cannot make the refrigerant completely condensed and air-conditioning rate is reduced by 40%. Drying effect increases in a faster rate and becomes stable (not affected by the water temperature).
- When the blower at the dryer and air-conditioning is switched off, the system work as a solar-assisted heat-pump water heater. The COP reduced by 36% in comparison to the mode using air-conditioning. The results indicated that air-conditioning contributed a considerable part of heating energy available at different condensers.

4 CONCLUSIONS

A solar assisted heat pump air conditioner, water heater, and dryer was designed and constructed. A series of experiments were conducted under the meteorological conditions of Singapore (tropics) to evaluate its performance under different applications and operating conditions.

For air-conditioning, the room temperature was maintained at 24^0C under the required cooling load of 3.2kW. This concludes that the system is able to provide the required cooling capacity. One important factor that affects the drying is drying air temperature. When drying air temperature increases, relative humidity of air will drop leading to a lower air partial pressure resulting a higher drying potential. A maximum SMER value of 0.613 kg/kWh was obtained in this experiment.

The solar collector efficiency varied between 0.60 and 1.70 and the maximum COP of the system was 4.58.

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