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PERFORMANCE EVALUATION OF SOLAR-ASSISTED DOUBLE-TUBE EVAPORATOR HEAT PUMP SYSTEM

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ABSTRACT

A new configuration of a solar assisted heat pump is presented and analyzed. The system employs a double-tube evaporator where solar collector water is pumped through an inner tube, and a refrigerant flows in the annular space between the inner and outer tubes. With such design characteristics, the air in addition to the water provides some heating of the refrigerant. An experimental work was carried out on an existing (R-134a) heat pump to study the different factors that affect its capacity and operation. Experimental results were used to develop a computer model to investigate the performance of the proposed solar assisted heat pump in Amman, Jordan during the winter season. The model is also very useful for evaluating and comparing the heat output of different solar water heating systems under local climatic conditions. **© 2004 Elsevier Science Ltd**

Introduction

Jordan depends almost totally on imports of oil to meet it energy needs. The energy bill consumes about 7.2% of the GDP [1]. This high cost is causing a big burden on the national economy, and may hinder future economic and social development. Part of the solution to this economic problem is to utilize Jordan's renewable energy resources like solar energy. A very promising application of solar energy in Jordan is its use for space heating systems [2]. One of the most common means of solar space heating is the solar assisted heat pump (SAHP). It is being adopted in many countries because of its superior coefficient of performance (*COP*) as compared to existing conventional heat pumps. In the SAHP system, a flat plate solar collector is used as a heat source for the heat pump evaporator. Therefore, SAHP solar collector efficiency will be higher than in the conventional solar water heater (SWH) due to the lower temperature of the inlet water. This decreases the collector losses and allows the use of single cover or bare collector. Many studies and tests have been carried out on the thermal performance of different arrangements between the heat pump and solar collector such as: parallel, series, and dual systems. Freeman et al. [3] found that series arrangement between the flat plate collector and the heat pump achieves the highest *COP*. Chaturvedi et al. [4] studied the performance of a series SAHP system for domestic hot water and found it to be more efficient than SWH collector. They referred this to the lower exergy losses in the SAHP system. Odeh et al. [5] carried out experimental tests on a series SAHP for space heating. The heat pump evaporator was dipped in a solar collector thermal storage tank to absorb heat from the surrounding water. They used the test to verify a method of calculating the minimum design limit for the collector area based on the second law of thermodynamics. The performance of SAHP for water heating was compared by Axaopoulos et al. [6] with a conventional thermo-syphon solar collector. They used a refrigerant filled bare solar collector to utilize both sensible and latent heat of ambient air as well as the solar radiation during daytime. They found that the performance of SWH is affected seriously by weather conditions, where as SAHP could operate with no significant variation at *COP* value of above 3. Kaygusuz K. [7] conducted different experiments on series and parallel heat pump systems for space heating. He used the experimental results to determine the seasonal heating performance and total energy consumption of the system during winter. A mathematical model of a SAHP developed by Kaygusuz K. [8] was verified with the experimental results and a good agreement was found. Hulin et al. [9] studied two configurations of SAHP: solar collector acting as the evaporator, and a floating-plate-collector in a fresh water solar pond system. They concluded that the *COP* of the later to be considerably higher than the first one. Hawlader et. al. [10] have presented an experimental study on the performance of solar assisted heat pump water heater-dryer system. Cervantes et. al. [11] conducted experimental work on solar assisted heat pump with direct expansion of the refrigerant within the solar collector. Huang and Chyng [12] have investigated integral type solar-assisted heat pump water heater operating with Rankine refrigeration cycle and a thermosyphon loop cycle. Morrison et al. [13] developed a correlation model to investigate seasonal performance of different water heater systems based on TRNSYS simulation package. They showed that the annual energy savings in the air-source heat pump water heater is lower than for flat plate SWH or solar-boosted heat pump water heaters.

In this study a different configuration of solar assisted heat pump is presented based on using a double-effect heating evaporator. The refrigerant in the evaporator absorbs heat from the surrounding air in addition to the water flowing in an inner tube. Hence, the total heat available to the condenser is increased. The proposed system is well suited to Amman where its climate is characterized by relatively high irradiation, clear skies, and mild ambient temperatures in winter. The average monthly sunshine duration exceeds 6.3 hours in January [14]. This allows SAHP to utilize both sources of heat to increase its *COP* and heating capacity.

Configuration of the SAHP System

A schematic diagram of the studied system is shown in Fig. 1. The system is designed to deliver hot air for space heating or drying process applications. Hot water generated by the solar collector is collected in a thermal storage tank to keep the system operating after radiation hours. Double tube evaporator (coil type) is used in the heat pump side to have double effect heating to the refrigerant. This design of evaporator is similar to the double-tube water-cooled condenser used in refrigeration systems [15]. Water from the storage is pumped through an inner tube, and a refrigerant flows in an annular space between the inner and outer tubes. Heat is absorbed by the refrigerant from both, the hot water, and the ambient air. During no radiation periods the collector loop is closed, and the evaporator receives heat from the storage tank via the by-pass circuit.

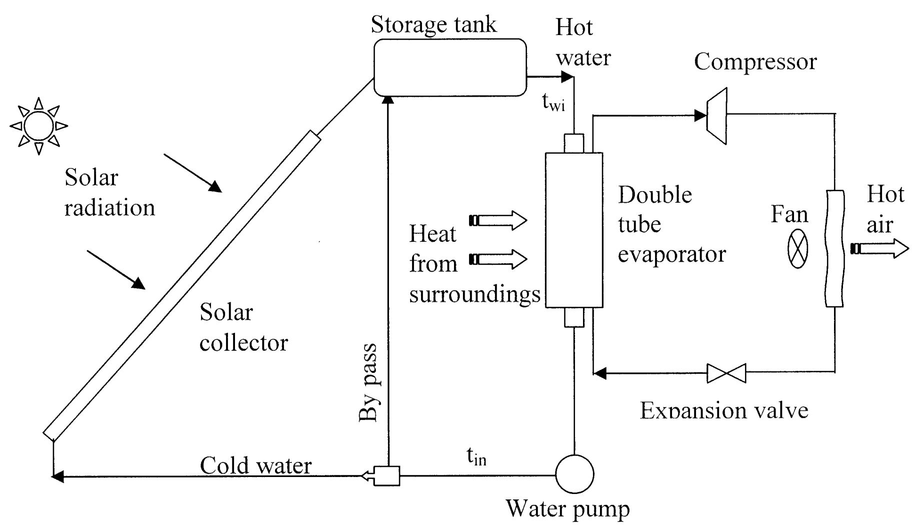

FIG. 1
The solar assisted heat pump with a double-tube evaporator.

Experimental Results

An experimental study on an existing (R134a) refrigeration rig with double-tube evaporator was carried out. The effects of different operating parameters (water flow rate, and temperature) on system performance were examined. These parameters were selected to achieve the highest efficiency of the solar collector. It is clear from Figure 2 that the increase of water flow rate (m_w) at ambient temperature will increase the heat rejected by condenser (Q_h) up to a level where optimum flow rate of 0.014 kg/s is obtained (Q_h is constant with flow rate). This water flow rate is within the range of optimum operating conditions of the solar collector and is used in the SAHP performance modeling. The temperature of the water inlet (t_{wi})at the evaporator also affects heat load as shown in Figure 3. Two different flow rates are selected and a linear relation between Q_h and t_{wi} is reported. Figure 4 shows the effect of increasing the heat delivered per gram of water (due to increase in m_w and t_{wi}) on heat rejected (Q_h), and heat absorbed (Q_l) in the cycle. The points of the lower part of Figure 4 were measured at ambient temperature, while other points cover tests performed at temperatures above ambient.

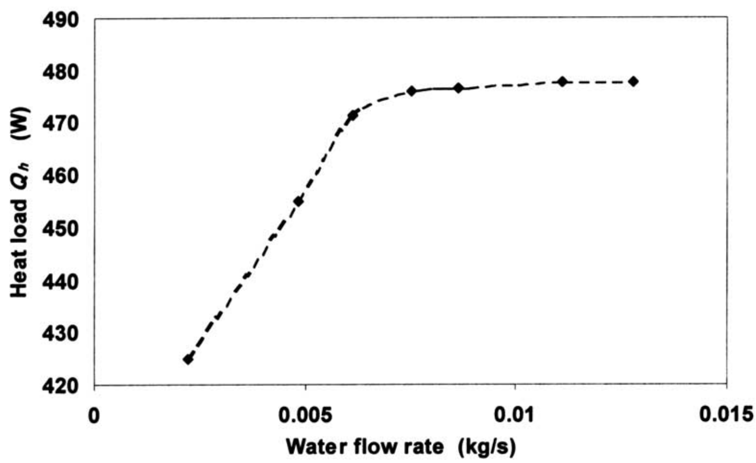

FIG.2
Effect of water flow rate on heat load

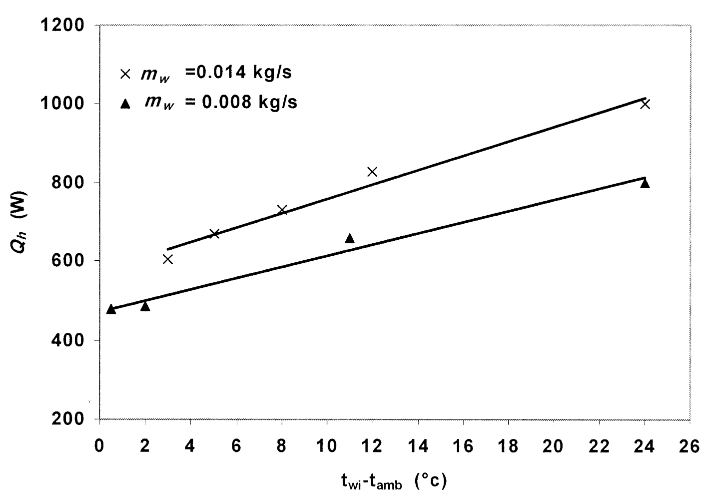

FIG.3
The effect of water temperature and water flow rate on heat rejected at condenser.

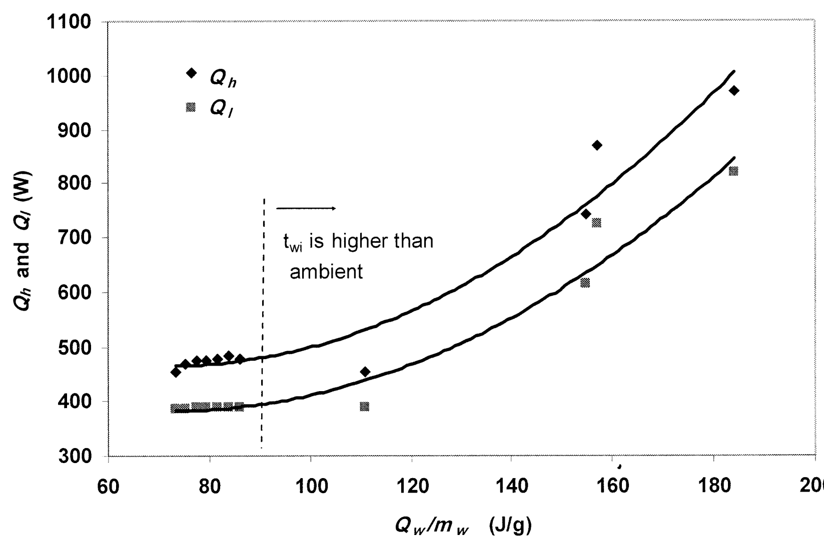

FIG.4
The effect of heat delivered per gram of water on Q_h and Q_l.

The effect of water temperature on the coefficient of performance (*COP*) was obtained and the results are shown in Figure 5. It is clear from this figure that *COP* is directly proportional to the inlet water temperature of the double-tube evaporator. A 25% increase in *COP* could be achieved if water temperature increases by 25°C above ambient. The effect of heat delivered ratio by water and surrounding air (Q_w/Q_l and Q_{amb}/Q_l) for different water to refrigerant flow rates (m_w/m_r) is shown in Figure 6. When t_{wi} increases, m_w/m_r decreases and heat delivered by water is reduced. However, as t_{wi} rises, more heat can be transferred at the condenser due to increased refrigerant flow rate. The effect of the ratio of water to refrigerant flow rate (m_w/m_r) on Q_w/Q_l and Q_{amb}/Q_l is shown in Figure 7. It is clear that when m_w/m_r increases, Q_{amb}/Q_l decreases and Q_w/Q_l increases due to the larger amount of heat delivered by water.

Computer Simulation

Computer modeling of the solar assisted heat pump is developed to investigate system performance during a typical winter day in Amman, Jordan. A standard solar collector (manufactured locally) is used as a heat source for the heat pump cycle. The collector was tested by the RSS [16] and its thermal efficiency was given by,

$$\eta_c = 0.6164 - 7.7858(t_{in} - t_{amb}) \quad (1)$$

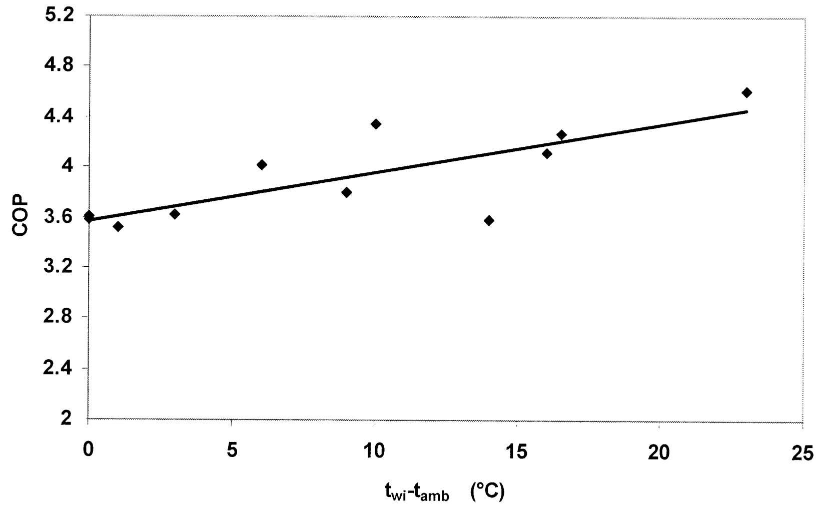

FIG.5
Effect of inlet water temperature on coefficient of performance.

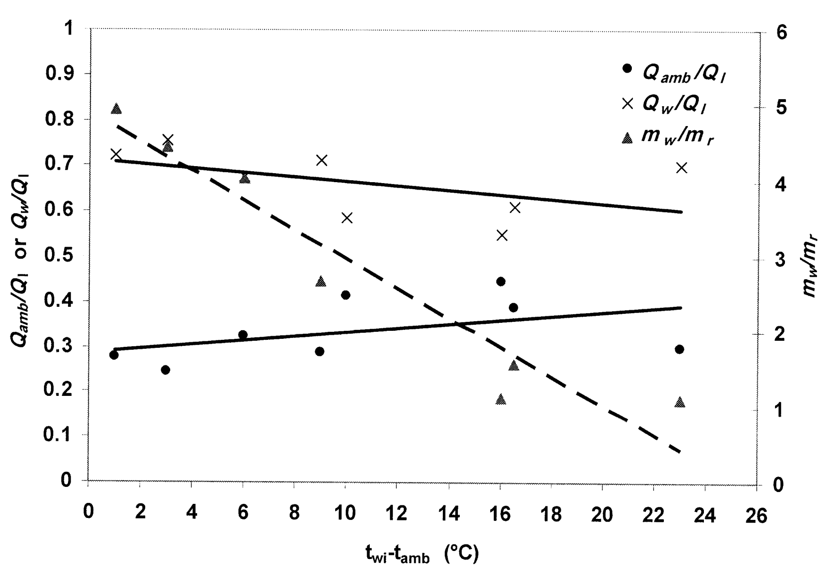

FIG.6
Effect of heat delivered ratio by water, surrounding air and water to refrigerant flow rates as function of temperature difference.

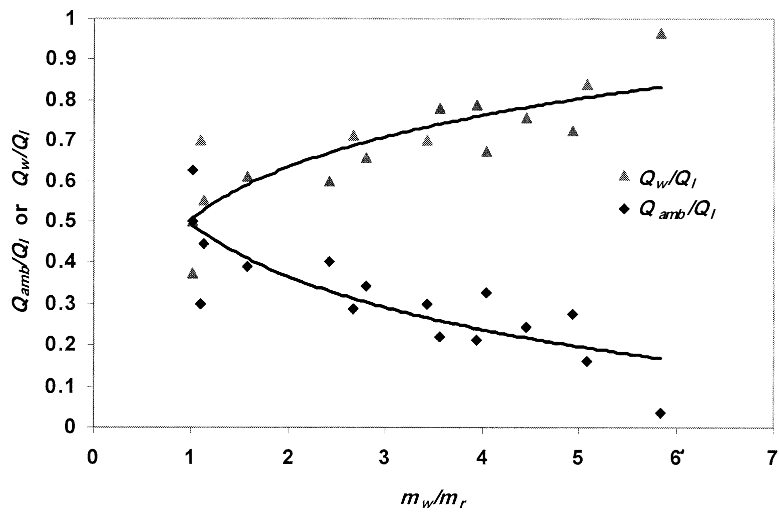

FIG.7
Effect of ratio of water to refrigerant flow rate on heat delivered by water and surrounding air.

Thermal storage tank is used to cover the load during off radiation periods. The temperature of water in the tank changes according to radiation level, heat load, and ambient temperature. The solution for the storage tank temperature (t_{stg}) during unsteady state condition is developed by a method similar to Duffie and Beckman [17], where:

$$\left(t_{stg}\right)^{j+1} = \left(t_{stg}\right)^{j} + \frac{\Delta time}{c_w * m_{stg}} * (Q_u - Q_l - Q_{loss}) \tag{2}$$

Correlations for Q_h, COP, and Q_w/Q_l are deduced from the experimental tests at different water and ambient temperatures. These are as follows:

$$Q_h = 24.373(t_{wi} - t_{amb}) + 537.88 \tag{3}$$

$$COP = 0.0385(t_{wi} - t_{amb}) + 3.5683 \tag{4}$$

$$\frac{Q_w}{Q_l} = 0.7136 - 0.0047(t_{wi} - t_{amb}) \tag{5}$$

$$\frac{Q_{amb}}{Q_l} = 0.2864 + 0.0047(t_{wi} - t_{amb}) \tag{6}$$

Equations 1 to 6 are used in a computer model to investigate the performance of a SAHP system using winter climatic data.

The effect of t_{stg} on *COP* of SAHP is illustrated in Figure 8. The peak *COP* occurs around 2 p.m. where maximum t_{stg} and Q_l are achieved. It can be noted from Fig.8 that the *COP* follows the trend of t_{stg} during the period of time prior to 8:00 p.m. This is because the storage tank temperature is higher than the ambient (t_{amb}). After 8:00 p.m. t_{stg} drops below t_{amb} and the effect of heat extracted from ambient air is higher than that from storage tank water which causes *COP* to follow t_{amb} trend. The heat output of the SAHP system per square meter of collector area is shown in Figure 9. It is clear that the heat delivered by the SAHP is significantly higher than the SWH which has limited operation hours. At the maximum output time (around 2:00 p.m.), the SAHP delivers 50% more heat than the SWH.

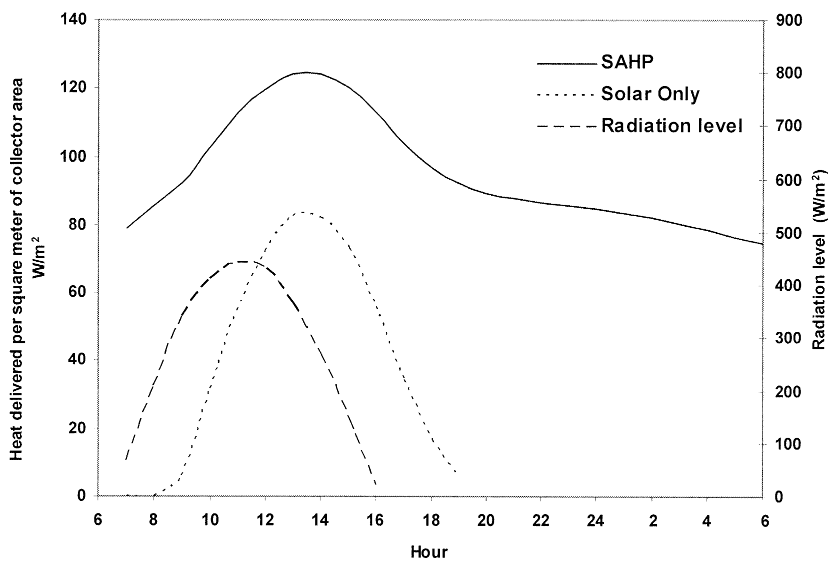

FIG.8
Comparison of hourly heat delivered per square meter of collector area between SAHP and SWH systems (collector area for both systems is $6m^2$).

The output ratio of different space heating systems with similar component sizes are evaluated and shown in Figure 10. The ratio of the delivered heat is taken with respect to the maximum heat delivered by the SAHP. It is clear from Figure 10 that the double effect system has superior performance to other systems. Its ratio varies between 0.7 and 1.0 during the 24 hours of operation

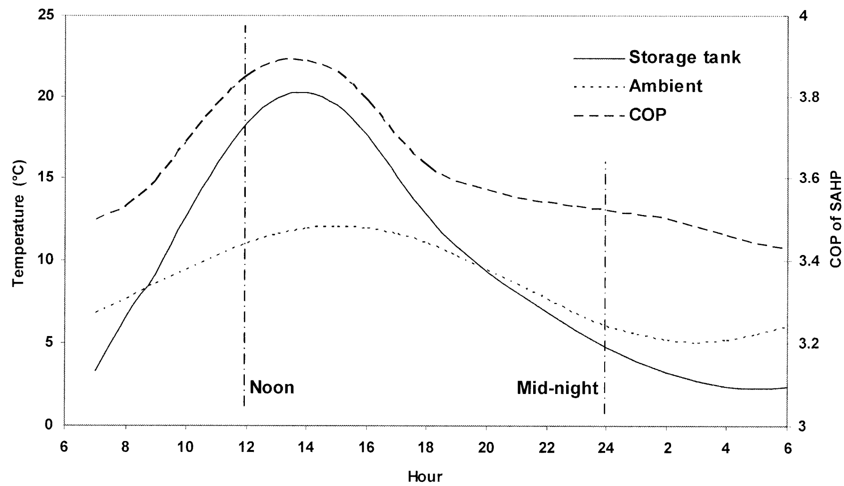

FIG.9
The effect of storage tank, and ambient temperatures on COP, (collector area is 6 m^2).

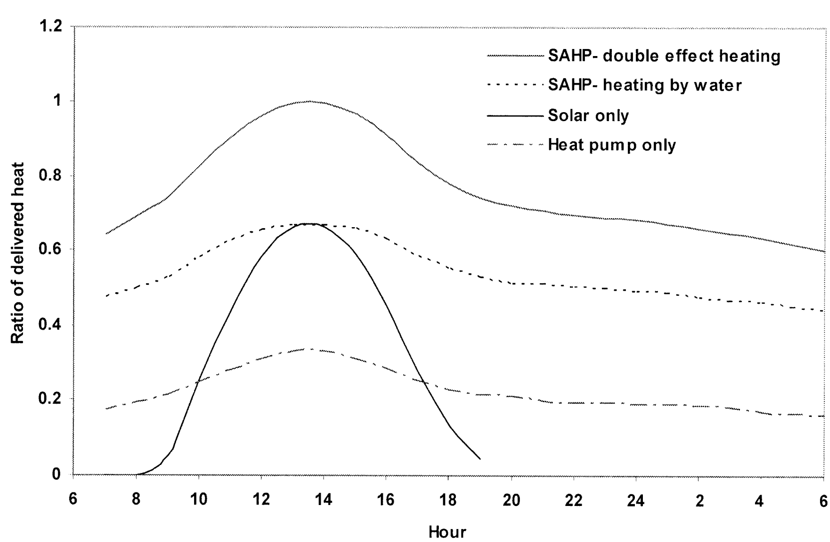

FIG.10
Output ratio of different space heating systems with respect to maximum heat delivered by SAHP of this study.

Conclusion

An alternative design of a solar assisted heat pump employing double-effect heating evaporator was presented. An experimental model of a heat pump was tested under different operating conditions similar to those of a standard solar water heater. The double effect heating evaporator was investigated by evaluating the ratio of heat transferred from surrounding air and water to the evaporator. The experimental results enabled us to optimize water temperature and flow rate in the evaporator and to deduce different correlations for system performance. These correlations were used to develop a computer model of the proposed system daily performance. The model also, compared the output ratio of different space heating systems under typical winter conditions in Amman- Jordan. The results showed that the heat delivered by the double effect heating system is significantly higher than other systems under local climatic conditions. Double-effect heating evaporator can collect energy from various sources: hot water from collector, latent heat released by condenser by condensation on the evaporator, sensible heat gain from atmosphere, and sensible heat gain from rain water passing over the evaporator when it is installed outdoors.

Nomenclature

COP	Coefficient of performance.	
Q_h	Heat rejected by condenser.	(W)
Q_l	Heat absorbed by evaporator.	(W)
Q_w	Heat delivered by water.	(W)
Q_{amb}	Heat delivered by ambient air.	(W)
Q_u	Useful energy gained by a collector.	(W)
Q_{loss}	Heat loss from storage tank to surroundings.	(W)
η_c	Solar Collector efficiency.	
m_{stg}	Mass of water in the storage tank.	(kg)
C_w	Specific heat of water.	(J/kgK)
t_{in}	Collector inlet temperature.	(°C)
t_{stg}	Storage tank temperature.	(°C)
t_{wi}	Evaporator inlet water temperature.	(°C)
t_{amb}	Ambient temperature.	(°C)
m_w	Water mass flow rate.	(kg/s)
m_r	Refrigerant mass flow rate.	(kg/s)
Δtime	Time interval.	(s)

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