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Investigation of a Solar Assisted Water Source Heat Pump System for Different Solar Radiations

Sezgi Koçak Soylu[#1], Çağdaş Çarkacı[#2], İbrahim Atmaca[#3], Ayla Doğan[#4]

[#]Mechanical Engineering Department, Akdeniz University
07058, Antalya, Turkey

[1]sezgikocak@akdeniz.edu.tr

[2] cagdascarkaci@gmail.com

[3]atmaca@akdeniz.edu.tr

[4]ayladogan@akdeniz.edu.tr

Abstract

In this study, experimental performance analysis of a solar assisted heat pump space heating system (SAHPSHS) installed in Antalya was performed for low (mean value of 55 W/m^2), moderate (mean value of 465 W/m^2) and high (mean value of 810 W/m^2) solar radiation. Antalya has a moderate climate and high solar radiation in winter thus, the highest heating requirement occurs after the sunset. Therefore, unlike common solar-assisted heat pump systems, a storage tank with 2-ton capacity was used for heat storage. The system was designed to operate also on the days when the solar radiation was insufficient thus, the tank temperature was lower than the limit value. In such days, storage tank was supplied by the city water as an auxiliary thermal source. For the performance evaluation, energy and exergy analysis is conducted. Thus, the coefficient of performance (COP) of heat pump and overall system and the exergy destruction rate of each component are determined. It is found out that the highest exergy destruction was occurred in the evaporator.

Keywords - solar energy; heat pump; experimental study; energy and exergy analysis

1. Introduction

The continuous increase of energy usage in all end-use sectors, plus globalization and climate changes obliged most of the countries to take an action on their energy policies. In this context, European Union (EU) developed several energy strategy plans (e.g. 2020 Energy Strategy [1], 2030 Energy Strategy [2], 2050 Energy Strategy [3]) and set energy efficiency targets. The 2020 and 2030 Strategies share same targets; reducing greenhouse gas emissions, increasing share of renewable energy and increasing energy savings, but with different levels of reach. Moreover, member countries need to reduce greenhouse gas emissions by 80-95% when compared to 1990 levels by 2050 [3].

In order to meet these targets, the EU Energy Commission had published several directives. The Eco-Design Directive [4] limits the design of both energy using (e.g. boilers, lamps, televisions and refrigerators), and related products (e.g. windows and insulation materials) to reduce energy consumption and damage to the environment. According to this directive, products must be labelled with an adequate information. The energy classes are named from A+++ to G and the products which are below class C are forbidden to sell since 26th of September 2015 [5]. As a natural outcome, the sales of class C and above products (e.g. condensing boilers, ***hybrid heat pumps***, cogeneration applications) were increased after this date. Therefore, heat pumps are finding increased usage in air-conditioning applications.

The policies and endeavour over the efficient use of energy in Turkey primarily started with the release of “Energy Efficiency Law” in 2007. The purpose of this law is to ensure efficient use of energy, preventing wastage, protecting environment and lowering energy costs. “Regulations on the Energy Performance of Buildings” was published within regarding law and introduced certain limitations to the energy use of buildings. Despite all the efforts, total energy imports increased more than 200% and costed almost 60 billion US dollars from 1990 to 2012 [6]. The reason behind this issue is both the shortcomings in regulation and the problems in execution of existing rules. Thus, there is an urgent need for Turkey for better strategies and enforcements regarding energy efficiency in buildings. The change is needed primarily for air-conditioning systems and also for energy using and related products [7]. In this context, increasing the use of renewable energy in buildings will lead to less energy consumption and CO_2 emissions.

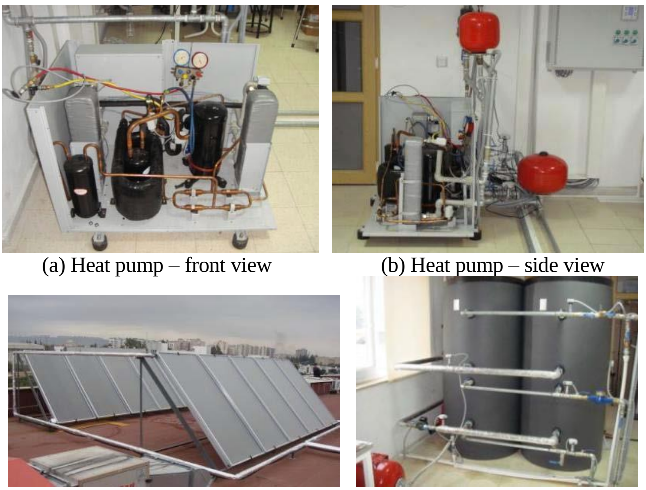
Heat pumps can operate with various heat sources such as air, water, ground or renewable energy like solar. The combination of solar thermal collectors and heat pumps is a very promising system in terms of increasing renewable energy usage at global scale [8]. Thus, they might be an answer for reducing energy consumption and gas emissions. Due to the specified reasons, research over heat pumps gained more attention during recent years. In one of these studies, a combined solar thermal and heat pump system for different buildings and a typical Central European climate is simulated [8]. Researchers compared the results of simulation with a reference case (i.e. without solar heat pump) to see the benefits of using solar collectors. Another experimental study performed on a SAHPSHS with a daily energy storage showed that COP of the heat pump is about 2.5 on a cloudy day while it was about 3.5 on a sunny day because of different storage tank temperatures [9]. In order to analyse the performance of a solar assisted heat pump under extremely cold climatic condition, Liu et al. [10] carried out an experimental study. Based on the field tests and optimization results, they determined that when the heating load is high and conventional heating cause great amount of pollution, solar heating is a considerable alternative. Solar heat pump systems have wide capacity range and can be sufficient for industrial heating. Suleman et al. [11] developed an integrated system to be used in textile industry and performed energy and exergy analyses. Their results showed that the energetic COP of the heat pump cycle and system are 3.54 and 2.97, respectively.

In this study, experimental analysis of a SAHPSHS is carried out. The system is installed in Antalya, Turkey and the effect of solar radiation is on the system performance is evaluated by considering 3 different solar radiation levels. Energy and exergy analysis is carried out hence, COP values and exergy destruction rate of each component are presented in the results section.

2. System Description

2.1 Experimental Setup

The experimental setup was built in Antalya at 36.91°N latitude to provide air-conditioning for 110 m^2 laboratory space. The cooling and heating loads of the regarding space were 15 kW and 5 kW, respectively. At the design conditions, heating and cooling capacity of the heat pump was 18.9 kW and 17.5 kW, respectively. The refrigerant used in the heat pump cycle was R410A. The basic elements of the setup were 10 solar collectors, 2 one-coil boilers (each with 1 m^3 capacity) and 3 circulation pumps. Several images regarding the experimental setup and its components are given in Fig. 1.



(a) Heat pump – front view (b) Heat pump – side view

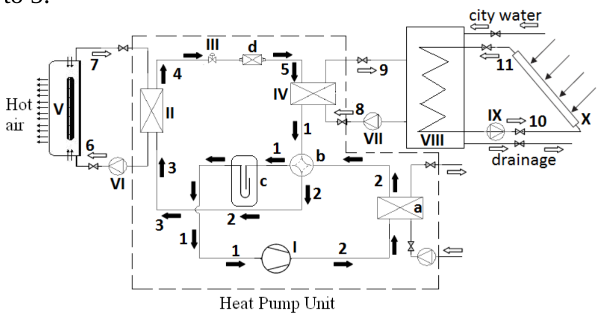
(c) Solar collectors (d) Heat storage tanks

Fig. 1 Components of solar assisted water source heat pump system

The collectors were copper tube type with an absorber surface area of 1.79 m^2. Absorber surfaces were 0.5 mm aluminium plates and galvanized to work as a selective surface. The cover glasses of the collectors had low iron content, providing 90.7% solar energy transmittance. The estimated optical efficiency of the collectors was around 81.1%. The collectors were installed as 2 parallel lines with 5 collectors in series in each line and the tilt angle was determined as 50°. One-coil boilers with 2 m^3 capacity in total were used for energy storage. The system consisted of three separate cycles driven by three circulation pumps. The three cycles in the system were; collector-heat pump, storage tank-heat pump and heat pump-fan coil.

2.2 Thermodynamic operation of the system

The schematic diagram of the system is given in Fig 2. The diagram shows the components of SAHPSHS and the thermodynamic operation is marked as 1 to 5.



I: Compressor, II: Condenser (1) for air-conditioner, III: Expansion valve, IV: Evaporator
V: Fan-coil unit, VI: Circulating pump I, VII: Circulating pump II, VIII: Heat storage tank
IX: Circulating pump III, X: Solar collector a: Condenser (2) for domestic hot water
b: Four-way valve, c: Gas-liquid separator, d: Non-return valve

Fig. 2 Schematic diagram of solar assisted heat pump space heating system

The operation begins at point 1 as the refrigerant comes of evaporator (IV) and draws energy from solar heated water (VIII). The refrigerant then moves to the compressor (I) and leaves it to pass through condenser 2 (a) which is used for hot water supply. After that, it reaches the condenser 1 (II) and releases heat to the fan-coil unit (V) for space heating purpose. Finally, after passing through the expansion valve (III), the refrigerant comes back to the evaporator and the cycle completes. It should be noted that Fig. 2 represents the entire operation but the refrigerant did not pass through condenser (2) since in this study, the operation was heating only.

3. Analysis

3.1 Test method

The heat pump system had three operational alternatives:

i. only cooling or cooling and hot water supply (summer operation)
ii. only heating or heating and hot water supply (winter operation)
iii. only hot water supply (mid-season operation)

In this study, the system operated in “only heating” mode. Due to the climatic characteristics of Antalya, heating requirement mostly occurs after the sunset. Therefore, the heating period was determined between 17:00 pm and 01:00 am. Automation system set as, by 17:00 pm, if the room temperature was under 20°C, heat pump started operating and stopped if it reached 24°C. These limitations were applied for 8 hours of operation.

During the day, thermal energy was stored in the tanks. The measurement system controlled the temperature difference between storage tanks and solar collectors. When the difference was 10°C, circulation pump started operating and transferred the energy stored in the collectors. The lowest water temperature in the storage tank for heat pump to operate was 10°C. On some days when the solar radiation was low and there was not enough thermal energy, the storage tank temperature dropped to 10°C. When this happened, the storage tank was supplied with city water at 15.4°C as an auxiliary thermal source. Thus, the heat pump was not allowed to stop operating. The better option would be using groundwater as an auxiliary thermal source instead of the city water. The reason for choosing city water as an experimental alternative is actually a necessity under the budget of this study. As it is known, in order to use groundwater, boreholes and piping system needs to be included which brings additional costs. Therefore, city water was used as an experimental representative for groundwater. The data was regularly monitored and recorded with data acquisition system at various time intervals. The information was processed through calculations to analyse the system.

3.2 Energy and exergy calculations

The processes are assumed to be steady-state, steady-flow, and the mass, energy and exergy balance equations are used to determine the heat input, the rate of irreversibility and the energy and exergy efficiencies [12,13].

The mass, energy and exergy balance equations can be expressed as,

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{2}$$

$$\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} - \sum \dot{Ex}_{dest} = 0 \tag{3}$$

where $\dot{m}$ [kg/s] is mass flow rate, $\dot{E}$ [kW] is energy rate and $\dot{E}_x$ [kW] is exergy rate.

The exergy rate can also be written using specific exergy (ex) [kJ/kg];

$$\dot{Ex} = \dot{m}(ex) \tag{4}$$

The specific exergy of each fluid is defined as,

$$ex = (h - h_o) - T_o(s - s_o) \tag{5}$$

where h [kJ/kg] is specific enthalpy, T [K] is temperature and s [kJ/kgK] is specific entropy. The subscript "0" stands for dead state.

The exergy efficiency is defined as the ratio of total exergy output to total exergy input;

$$\psi = \dot{Ex}_{out}/\dot{Ex}_{in} = \dot{P}/\dot{F} \tag{6}$$

where "out" stands for "net output", "*product*", "desired value" or "benefit" and "in" refers to "given", "used" or "*fuel*" [14].

Van Goal's improvement potential is expressed as [13],

$$I\dot{P} = (1 - \psi)\left(\dot{Ex}_{in} - \dot{Ex}_{out}\right) \tag{7}$$

The balance equations of mass, energy and exergy along with the exergy efficiency and improvement potential values for each component of the water source heat pump space heating system are obtained by (1) – (7). The first law efficiency (COP) for heat pump unit and overall system are calculated by;

$$COP_{HP} = \dot{Q}_{cond}/\dot{W}_{comp,elec} \tag{8}$$

$$COP_{system} = \dot{Q}_{cond}/\dot{W}_{comp,elec} + \dot{W}_{pumps} \tag{9}$$

4. Results and Discussion

The daily mean rate of evaporator energy gain, energy rejected from condenser and compressor power are calculated with the first law of thermodynamics and equation of continuity. The results of these calculations are given in Fig 3 (a). As can be seen from the figure, system had the highest heating capacity (i.e. energy rejected from condenser) when the solar radiation was moderate. The daily mean values of the Q_{cond} were 15.45 kW, 18.62kW and 17.55kW for low, moderate and high solar radiation, respectively. Likewise, both Q_{evap} and $W_{comp,elec}$ had their highest values on moderate solar radiation. Heat pump and overall system COP are also given in Fig 3 (b). Although the highest condenser power was obtained on moderate solar radiation, the lowest COP for both heat pump and overall system were also determined on moderate radiation. COP_{hp} had its maximum value on low solar radiation as 2.99, while it was 2.90 and 2.86 for high and moderate radiation, respectively.

The order was similar for system COP as shown in Fig 3 (b). The reason for high COP under low radiation was the low electrical power consumption of the compressor. The daily mean power consumption of the compressor was 5.16 kW, 6.06 kW and 6.51 kW for low, high and moderate solar radiation, respectively. The power consumption of 2 circulation pumps was considered constant as 0.39 kW and 0.25 kW. Fig 3 (b) shows that COP values for each solar radiation level were almost the same. The reason is on low solar radiation day, the storage tank was supplied by city water thus, the temperature did not drop too much. The different solar radiation levels had significant effect on the storage tank temperature. When the solar radiation was low, the tank temperature decreased to 10°C and lower. Therefore, the tank was supplied by city water which was around 15°C. Thus, the degradation of the heat pump and an interruption in the heating system was avoided. This situation was only occurred for the low solar radiation case. For real applications it is better to use groundwater as an auxiliary thermal source instead of city water.

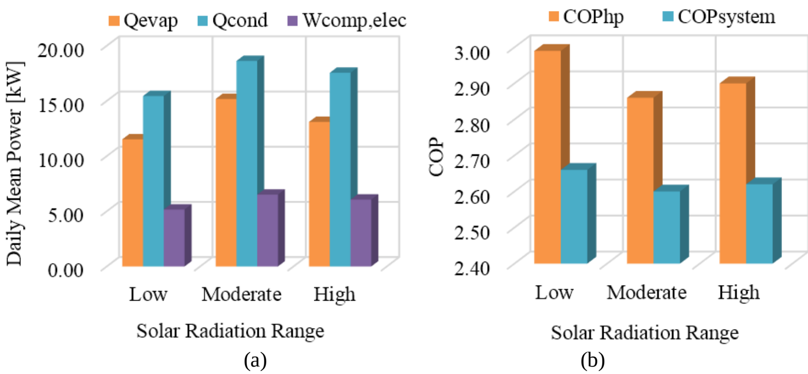


Fig. 3 Change of daily mean power rates of evaporator, condenser and compressor (a) and heat pump and overall system COP values (b) with different solar radiations

Exergy analysis is evaluated with respect to a reference environment or a dead state. In this study, the dead states considered as the daytime mean outlet temperatures for each respective day of different solar radiation. These values were measured as 11.1°C, 13.8°C and 9.3°C for low, moderate and high solar radiation, respectively. The restricted dead state pressure was considered 1 bar for atmospheric conditions of each case. Exergy destruction and improvement potential rates of each component of the system are given in figures 4,5 and 6 for different solar radiation levels.

It is clear from Fig. 4, 5 and 6 that the greatest irreversibility was occurred in evaporator among the heat pump components and fan-coil unit compared to all other system elements. High temperature difference between the working fluid and the storage tank water as well as 1 bar pressure drop in the heat exchanger caused evaporator irreversibility. Similarly, fan-coil unit also works with high temperature difference which results in increased exergy destruction rates. In order to avoid high irreversibility that fan-coil unit causes, a different space heating approach such as floor heating might be preferred.

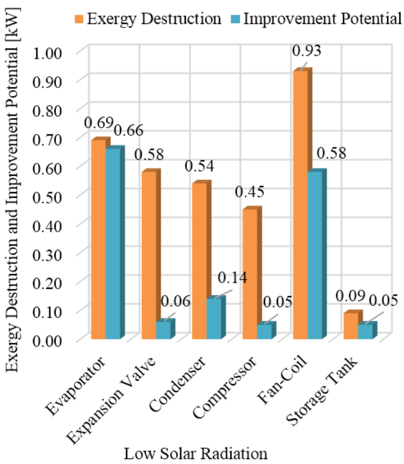


Fig. 4 Exergy destruction and improvement potential rates of each component of the system for low solar radiation

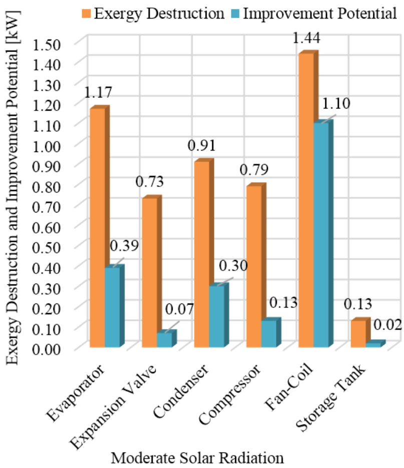


Fig. 5 Exergy destruction and improvement potential rates of each component of the system for moderate solar radiation

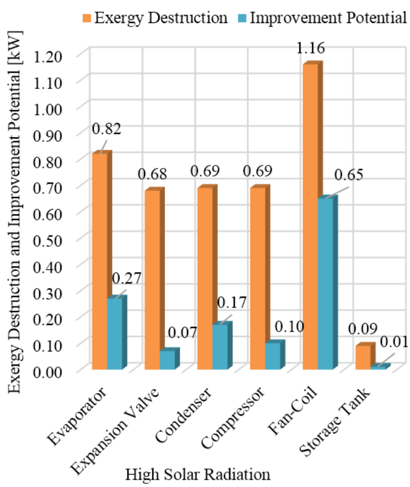


Fig. 6 Exergy destruction and improvement potential rates of each component of the system for high solar radiation

The highest irreversibility is same for each solar radiation case, but rest of the order changes. When the system operated under low solar radiation, irreversibility lined up as evaporator, expansion valve, condenser and compressor from highest to lowest. But in case of moderate and high solar radiations, condenser had the second irreversibility followed by compressor and expansion valve.

As above mentioned, improvement potentials of the system components are also presented on the same set of figures. As a result of exergy destruction rates and second law efficiencies, the greatest improvement potential is existed in the fan-coil unit followed by evaporator, condenser, compressor, expansion valve and storage tank. The equipment which has high irreversibility especially needs to be improved since it considerably reduces overall system performance. Temperature differences between the two fluids, pressure drops and flow imbalance lead to irreversibility in the heat exchangers (e.g. evaporator and condenser). The improvement of heat exchangers to reduce condensing and evaporating temperature difference would decrease the electrical input of compressor. However, any improvement in motors, valves, lubrication or a supplying an effective cooling can also reduce the compressor power. The compressor electrical input depends strongly on inlet and outlet pressures.

5. Conclusion

In this study, an experimental analysis of SAHPSHS installed in Antalya was performed for different solar radiation levels. The energy and exergy analysis is carried out, thus COP values and exergy destruction rate of each component are given. COP_{hp} had its maximum value on low solar radiation as 2.99, while it was 2.90 and 2.86 for high and moderate radiation, respectively. Therefore, the mean COP_{hp} was 2.92 which is in the range of an approximate value for a SAHPSHS as stated by Yumrutaş and Kaşka [9]. In addition, mean value for COP_{system} was calculated as 2.63. Although it should be kept in mind that the operating strategy of this study is different than the conventional approach of using solar heated water simultaneously. Therefore, the COP values might be slightly different than the conventional SAHPSHS.

The results of exergy analysis showed that the highest irreversibility and improvement potential is occurred in evaporator between heat pump components and fan-coil unit regarding the entire system. Authors believe that using floor heating instead of fan-coil would reduce the exergy destruction rates and could improve overall system performance.

Acknowledgment

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