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Solar Energy Assisted Heat Pump Water Heater

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ABSTRACT

A solar energy-assisted heat pump water heating system has been developed to improve household water heating efficiency. The system consists of a compressor, evaporator, capillary pipe, and condenser wrapped around a tank to avoid leakage. This study aims to evaluate the performance of the system through coefficient of performance (COP) measurements at 30 liter and 60 liter tank capacities. The test was conducted for five days with sunny weather conditions and data collection on temperature, solar radiation, and compressor power between 10:00 am and 2:00 pm. The results showed that the highest COP of 2.46 was obtained at a capacity of 60 liters, while 1.25 for a capacity of 30 liters. An increase in the final water temperature led to a decrease in COP, indicating that the system is more efficient at lower temperatures. This system shows the potential of utilizing renewable energy for efficient and economical water heating for household applications.

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Sebuah sistem pemanas air dengan pompa panas berbantuan energi surya telah dikembangkan untuk meningkatkan efisiensi pemanas air rumah tangga. Sistem ini terdiri dari kompresor, evaporator, pipa kapiler, dan kondensor yang dililitkan pada tangki untuk menghindari kebocoran. Penelitian ini bertujuan untuk mengevaluasi kinerja sistem melalui pengukuran coefficient of performance (COP) pada kapasitas tangki 30liter dan 60 liter. Pengujian dilakukan selama lima hari dengan kondisi cuaca cerah dan pengambilan data temperatur, radiasi matahari, dan daya kompresor pada pukul 10.00 pagi hingga 14.00 siang. Hasil penelitian menunjukkan bahwa COP tertinggi sebesar 2,46 diperoleh pada kapasitas 60 liter, sedangkan 1,25 untuk kapasitas 30 liter. Peningkatan temperatur air akhir menyebabkan penurunan COP, yang mengindikasikan bahwa sistem ini lebih efisien pada temperatur yang lebih rendah. Sistem ini menunjukkan potensi pemanfaatan energi terbarukan untuk pemanas air yang efisien dan ekonomis untuk aplikasi rumah tangga.

I. Introduction

Energy is one of the basic human needs in everyday life, both in the industrial and household sectors. In Indonesia, most energy use still relies on non-renewable fossil fuels, whose availability is dwindling. Therefore, the development and utilization of renewable energy sources, such as solar energy, becomes very important to support environmentally friendly energy sustainability [1],[2]. Indonesia, located along the equator and between a stack of tectonic plates, has large and stable geothermal and solar energy potential throughout the year [3].

Solar energy can be utilized in various applications, one of which is in water heating systems. In daily life, hot water is an important requirement for household needs such as bathing and washing, as well as for industrial needs, hospitals, hotels, and swimming pools [4]. Currently, hot water production is generally still dependent on electrical energy and fossil fuels, whose availability is limited. Therefore, innovations in water heating technology that are more efficient and environmentally friendly are needed, one of which is through the utilization of solar collectors and heat pump systems.

One of the technologies developed is the Direct Expansion Solar-Assisted Heat Pump Water Heater (DX-SAHPWH). This system combines a solar collector that functions simultaneously as an evaporator with a heat pump to increase water heating efficiency [5] [6]. To provide an overview of the configuration of the solar-based DX-SAHPWH system, it is shown in Figure 1.

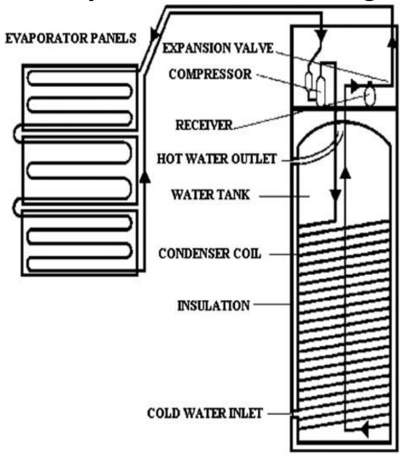

Fig. 1. Schematic of DX-SAHPWH system with solar-based integrated collector/evaporator [7].

In Figure 1, the DX-SAHPWH system uses a flat collector that directly functions as an evaporator. Heat energy from solar radiation is absorbed by the collector, heating the refrigerant inside. The heated refrigerant is then compressed to increase its temperature and pressure, before the heat is transferred to the water in the storage tank through the condenser. This process repeats in a closed cycle, enabling the production of hot water with high energy efficiency.

In addition to the integrated configuration, there is also a DX-SAHPWH system scheme with components separated in a more structured manner. This configuration is widely used in research to increase system flexibility and performance optimization [8] [9]. The basic schematic of the system with separated components is shown in Figure 2.

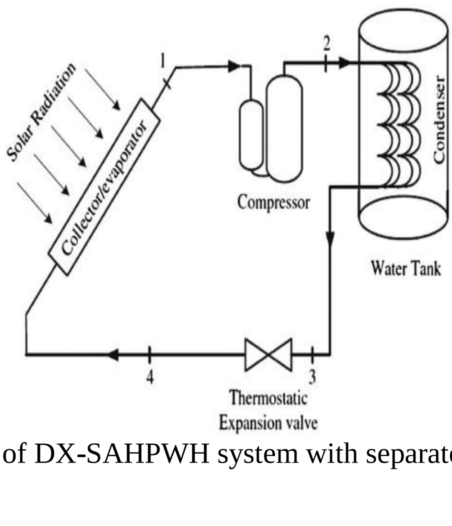

Fig. 2. Schematic of DX-SAHPWH system with separate components [10]

In Figure 2, the DX-SAHPWH system consists of a collector/evaporator to capture solar energy, a compressor to increase refrigerant pressure, a condenser to transfer heat to water, and an expansion valve to reduce refrigerant pressure before returning to the evaporator [11]. This configuration allows for more flexible and efficient system performance settings according to operational needs.

Various studies have shown the great potential of DX-SAHPWH systems. Li conducted a performance analysis of a system with a 4.20 m² direct expansion type collector, resulting in a coefficient of performance (COP) of 6.61 in heating 150 liters of water [12]. found that system performance was strongly influenced by variations in solar radiation, ambient temperature, and compressor speed [10]. Amin reported that a non-glazed evaporator collector in Singapore was able to achieve 80-90% efficiency with a COP of 8.0 [13]. In addition, Kong XQ showed that the use of R-134a refrigerant as well as a variable frequency compressor can improve system performance, especially under high radiation intensity conditions [14].

However, most of the previous DX-SAHPWH studies used large-sized collectors, about 4.2 m², which are less practical for household applications as they require large space and high investment costs. To date, there are still few studies that evaluate the performance of DX-SAHPWH systems with small-sized collectors. For this reason, this study aims to analyze the experimental performance of the DX-SAHPWH system using a small collector measuring 0.23 m² with variations in tank capacity of 30 liters and 60 liters. In addition, this study also aims to evaluate the effect of solar radiation intensity, ambient temperature, and final water temperature on the coefficient of performance (COP) of the system, so as to provide recommendations for the development of an efficient and feasible solar energy-based water heating system applied on a household scale.

II. Reseach Metodhology

This study used a quantitative experimental approach to evaluate the performance of a Direct Expansion Solar-Assisted Heat Pump Water Heater (DX-SAHPWH) system with a small 0.23 m² collector and two variations of water storage tank capacity, namely 30 liters and 60 liters. The system was tested under real conditions to assess the efficiency of solar energy-based water heating, focusing on space- and cost-efficient household-scale applications.

2.1 Location and Time of Research

The study was conducted in Semarang City from September to October 2024, in an open area that allows optimal exposure to solar radiation. Data was collected every day from 10:00 a.m. to 2:00 p.m., which is when the intensity of solar radiation is at its highest, so that the data obtained represents the performance of the system under the best environmental conditions.

2.2 Research Variables

The variables in this study consist of three types, namely independent variables, dependent variables, and control variables. The independent variable in this study is the capacity of the water storage tank, which is varied between 30 liters and 60 liters to determine its effect on the performance of the DX-SAHPWH water heating system. The dependent variables include the coefficient of performance (COP) and the final water temperature, which are the main indicators of the success of the heating process. Meanwhile, the control variables are parameters that are kept constant during the test to make the measurement results more valid. The control variables include the area of the solar collector (0.23 m²), the type of refrigerant used (R-134a), the system pressure, and environmental conditions such as solar radiation intensity and ambient air temperature during the test. By controlling these variables, the effect of tank capacity variation on system performance can be observed objectively and accurately.

2.2 Research Tools and Materia

The equipment used in this study consists of a DX-SAHPWH system, which includes a collector/evaporator, rotary-type compressor, micro-channel condenser, and electronic expansion valve. The system uses R-134a refrigerant. Water temperature data is measured using a K-type digital thermocouple, which is connected to a data logger for automatic recording. A pyranometer is used to measure the intensity of solar radiation. All tools were set up in such a way as to ensure accurate and consistent measurements throughout the experiment.

Table 1. specifications of tools used in the study

Tools	Specifications
Type K Thermocouple	Temperature range: -200°C to 1372°C, Accuracy: ±1°C
Pyranometer	Measuring range: 0-2000 W/m², Accuracy: ±5%
Data Logger	8 channels, accuracy ±0.1°C, reading speed: 1 second
Solar Collector	Area 0.23 m², integrated with evaporator
Compressor	Rotary type, input power 0.75 kW

2.4 Data Collection Technique

Data collection in this study was carried out using the experimental method through direct observation of the performance of the DX-SAHPWH system. The main instruments used include a K-type digital thermocouple to record water temperature, a solar power meter to measure the intensity of solar radiation, and ampere pliers to determine the electrical power consumption by the compressor. In addition, a stopwatch was used to record the heating time, while digital scales and measuring cups were used to determine the exact mass and volume of water. Data were collected for five consecutive days under three different environmental conditions: outdoor, indoor without air conditioning, and air-conditioned. Measurements were focused between 10:00 am and 2:00 pm to maximize exposure to sunlight. Each test scenario was repeated up to five times to obtain consistent and reliable data. Secondary data sources were also used, in the form of literature reviews from scientific journals, books, and relevant academic documents.

2.5 **Data Analysis Technique**

The data obtained were analyzed quantitatively. The analysis was conducted by calculating the coefficient of performance (COP) value, which is the ratio between the heat energy absorbed by the water and the electrical energy consumed by the compressor. Thermal energy is calculated based on the mass of water, the specific heat capacity of water, and the increase in water temperature. While electrical energy is calculated from compressor power and operating time. The results of the calculations are then presented in the form of tables and graphs to illustrate the relationship between variables such as final water temperature, ambient temperature, and COP value. This presentation aims to facilitate data interpretation and drawing conclusions about system efficiency in various environmental conditions.

III. Result and Discussion

This study aims to evaluate the experimental performance of the Direct Expansion Solar-Assisted Heat Pump Water Heater (DX-SAHPWH) system using a small collector measuring 0.23 m² with variations in tank capacity of 30 liters and 60 liters, and evaluate the effect of environmental conditions, solar radiation intensity, and final water temperature on the coefficient of performance (COP) of the system.

3.1 Water Temperature Performance

The tests showed that the highest water temperatures were obtained under outdoor conditions, 49.54°C (30 L) and 49.44°C (60 L), as the collectors received direct solar radiation. In indoor conditions without air conditioning, the final temperatures decreased to 44.14°C (30 L) and 42.90°C (60 L), while in the air-conditioned room the temperature only reached 39.20°C for both capacities.

Table 2. Final water temperature based on tank condition and capacity

Conditions	Capacity	Final Temperature (°C)
Outdoor	30 L	49,54
Indoor	30 L	44,14
Air-conditioned room	30 L	39,20
Outdoor	60 L	49,44
Indoor	60 L	42,90
Air-conditioned room	60 L	39,20

3.2 System COP Value Based on Tank Capacity

The highest COP was achieved in the outdoor test, which was 1.25 (30 L) and 2.46 (60 L). In contrast, in the air-conditioned room, the COP decreased dramatically to 0.60 (30 L) and 1.19 (60 L). This difference is due to the decrease in solar radiation and ambient temperature, so the refrigerant absorbs less heat.

Table 3. System COP Value Based on Tank Capacity

Conditions	Capacity	Final Temperature (°C)
Outdoor	30 L	1,25
Indoor	30 L	0,90
Air-conditioned room	30 L	0,60
Outdoor	60 L	2,46
Indoor	60 L	1,52
Air-conditioned room	60 L	1,19

3.3 Effect of Solar Radiation Intensity on COP

In the 30 liter and 60 liter outdoor tests, the test was carried out 5 times on different days, so the average solar radiation intensity in each test was different. The intensity of solar radiation varies in the 30 liter test from 928.18 W/m2 in outdoor test 1, 920.45 W/m2 in outdoor test 2, 922.64 W/m2 in outdoor test 3 949.35 W/m2 in outdoor test 4, and 973.30 W/m2 in outdoor test 5, with an average ambient temperature in each test of ± 34 oC. Solar radiation intensity has an important influence on the performance of solar energy-assisted heat pump water heating systems using R134a refrigerant.

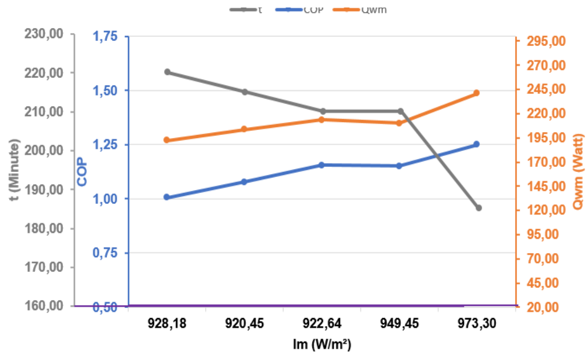

Fig. 3. Graph of 30 Liter Capacity of the Effect of Solar Radiation Intensity on COP

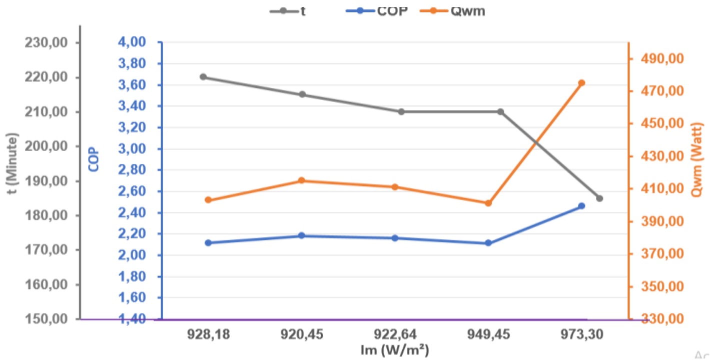

Fig. 4. Graph of 60 Liter Capacity of the Effect of Solar Radiation Intensity on COP

In Figure 3, it can be seen that an increase in the intensity of solar radiation results in an increase in the coefficient of performance (COP) by 4.8% in a system with a capacity of 30 L. In addition, the time required for heating decreases by 15.90%, and the heat transfer rate of water ($\dot{Q}$wm) increases by 25.35%. An increase in the intensity of solar radiation accelerates the condensation process on the evaporator, which results in an increase in system efficiency. Whereas in Figure 4 for a capacity of 60 L, an increase in radiation intensity also results in an increase in COP of 4.8%, with a reduced heating time of 15.90% and an increase in $\dot{Q}$wm of 14.48%. This shows that solar radiation intensity greatly affects the efficiency of the DX-SAHPWH system, although the magnitude of the effect on the heat transfer rate is relatively smaller at larger tank capacities. fluctuated between 750-1020 W/m² during the test. On days with the highest intensity, the COP tended to increase, especially for the 60 L capacity. This indicates that the higher the solar radiation received by the collector, the greater the heat absorbed by the refrigerant, thus increasing the system efficiency.

3.4 Effect of Environmental Temperature on COP

Testing of 30 liter capacity and 60 liter capacity is done in three different places, namely outdoors, in a closed room, indoors with air conditioning. This is done to get the difference in ambient temperature at the time of testing. The effect of ambient temperature on the performance of the solar energy-assisted heat pump water heating system using R134a refrigerant can be seen in Figures 5 and 6 below.

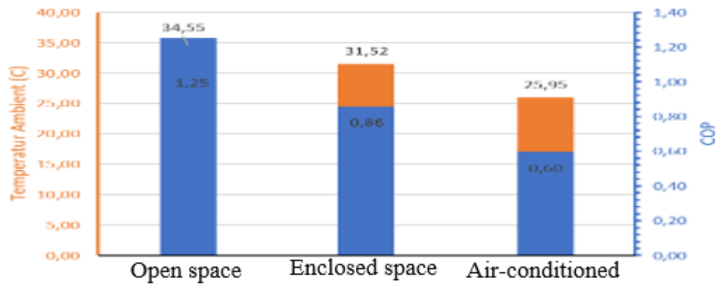

Fig. 5. Graph of 30 Liter Capacity Effect of Environmental Temperature on COP

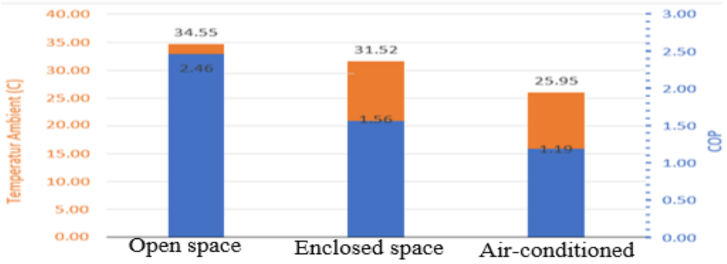

Fig. 6. Graph of 60 Liter Capacity Effect of Environmental Temperature on COP

Based on Figure 5, the highest coefficient of performance (COP) value was obtained in the test in an open space exposed to sunlight, with an average ambient temperature of 34.55 °C, which amounted to 1.25. Meanwhile, the lowest COP value was recorded in the test in a closed room with air conditioning, at an average temperature of 25.95°C, which amounted to 0.60. Furthermore, in Figure 6, the highest COP value was also obtained in the open space test with an average temperature of 34.55 °C, which amounted to 2.46. The lowest COP value was recorded in a closed room with air conditioning at an average temperature of 25.95°C, which amounted to 1.19. Ambient temperature has no significant effect on the solar energy-assisted heat pump water heating system. This can be seen from the comparison of COP values between the closed room without conditioning (average temperature 31.54 °C) and the closed room with air conditioning (25.95 °C), which shows a relatively small difference in COP values. In contrast, testing in an open space with direct exposure to sunlight showed much higher COP values, indicating a large influence from the intensity of solar radiation.

3.5 Effect of Water End Temperature on COP

In one of the tests with a capacity of 30 liters and 60 liters outdoors exposed to direct sunlight, with an average radiation intensity of 973.30 W/m² and an average ambient temperature of 34.55 °C, a graph was made to see the effect of the final water temperature on the performance of a solar energy-assisted heat pump water heating system using R134a refrigerant.

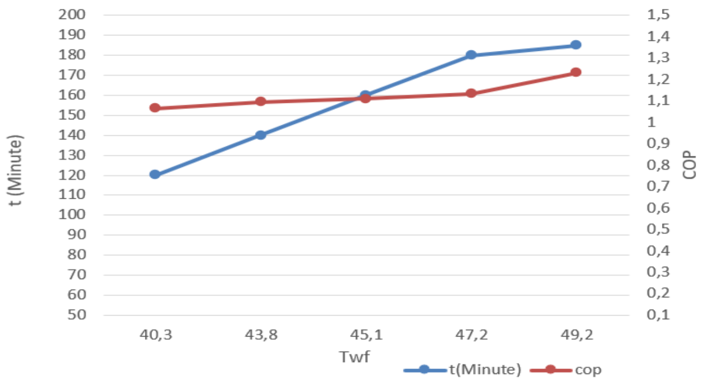

Fig. 7. Graph of 30 Liter Capacity Effect of Final Water Temperature on COP

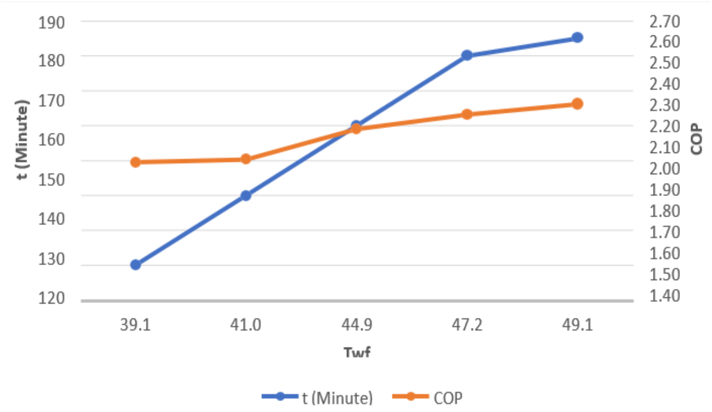

Fig. 8. Graph of 60 Liter Capacity Effect of Final Water Temperature on COP

Based on Figure 7, with an initial water temperature of 28 °C, it can be seen that the higher the final water temperature, the system performance or coefficient of performance (COP) of the solar energy-assisted heat pump water heater with R134a refrigerant tends to decrease, while the heating time (τ) required is getting longer. When the final temperature increases from 40.3°C to 49.2°C, the COP decreases by 16.03%, while the heating time increases by 54.1%. Similarly, in Figure 8, with the same initial water temperature (28°C), increasing the final temperature from 39.1°C to 49.1°C causes a decrease in COP by 25.62%, and an increase in heating time by 54.16%. This shows that the lower the desired final water temperature, the better the system performance (COP) and the shorter the heating time required.

3.6 Comparison with Previous Research

The results of this test were then compared with the results of previous research by Kong XQ, which analyzed the experimental performance of a direct-expansion solar assisted heat pump water heater with R134a refrigerant in summer [14]. The system used in Kong XQ research has a capacity of 200 liters, consisting of a flat plate collector/evaporator with a surface area of 2.1 m², a 420 Watt compressor, a 0.2 m³ capacity hot water tank surrounded by a micro-channel condenser, and an electronic expansion valve. A comparison of the results of the two tests is presented in Table 4, which shows the difference in performance of each system.

Table 4. Comparison of Test Results

Testing Results	Highest Coefficient of Performance (COP)	Effect of Increased Solar Radiation Intensity	Effect of Increasing Final Temperature
Capacity 30 Liter	1,25	COP Increased 4.8%	COP Reduced 16.03%
Capacity 60 Liter	2,45	COP Increased 4.8%	COP Reduced 25,62%
Kong XQ	5,68	COP Increased 28,3%	COP Reduced 20,8%

Based on Table 4, there is a difference in results between the tests conducted in this study and the previous study by Kong XQ. In the current test, the highest coefficient of performance (COP) value was recorded at 1.25 for a capacity of 30 liters and 2.45 for a capacity of 60 liters. Meanwhile, in Kong XQ research, the highest COP value reached 5.68 [14]. This shows that the COP value of the current test is lower than the results of previous studies. In the 30-liter capacity test, an increase in the final water temperature from 40.4°C to 49.2°C caused a decrease in COP of 16.03%. While at a capacity of 60 liters, the increase from 39.1 ° C to 49.1 ° C causes a decrease in COP of 25.62%. Meanwhile, Kong XQ (2018) reported that increasing the intensity of solar radiation increased the COP by 28.3%, while in this test, increasing the radiation intensity only increased the COP by 4.8%. In addition, increasing the final water temperature from 50°C to 60°C in this test also caused a 20.8% decrease in COP, indicating that the higher the final water temperature, the more the system performance decreased.

IV. Conclusion

This research shows that solar radiation intensity plays an important role in improving the performance of the DX-SAHPWH water heating system. The higher the radiation intensity, the faster the rate of heat transfer to the water, making the heating process more efficient. The highest coefficient of performance (COP) value at the 30-liter tank capacity was 1.25, while at the 60-liter capacity it reached 2.46, both obtained from outdoor tests exposed to direct sunlight. In contrast, the lowest COP values of 0.60 and 1.19 were found in the air-conditioned tests, respectively. This indicates that optimal system performance is achieved when the collector receives direct exposure to solar radiation. In addition, the results also showed that the difference in ambient temperature between the ordinary closed room and the air-conditioned room did not have a significant effect on the COP, when compared to the direct effect of solar radiation intensity. Finally, the tank capacity also affects the COP; larger capacity tanks tend to produce higher COPs, as the heat transfer process is more stable at larger volumes of water.

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