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# Experimental Assessment of Air-Source and Hybrid Ground-Source Heat Pump Systems

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## Abstract

Ground-source heat pump air conditioning systems are more efficient than air-source air conditioning systems in terms of energy consumption. Optimal hybrid utilization of air and ground heat sources has been shown to reduce the heat load on the ground. This study aims to ascertain the performance of hybrid heat pump systems in comparison to the standard air-conditioning system. A field test was conducted for the hybrid air conditioning and air-source systems. For the experiment, two commercial air conditioners were utilized. One of them was set up as a standard air-source air conditioner. Another one was connected with the ground to construct a ground-coupled hybrid air conditioner. The experimental setup was constructed in two small houses, one for each heat pump system. Generally, a hybrid heat pump system performs better over time compared to an air-source system. So, a comparison test between an air-source heat pump and a hybrid heat pump for cooling conditions was conducted to validate this point. The hybrid heat pump system showed an overall higher coefficient of performance (COP) compared to the air source air conditioning system.

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*Keywords: ground-source heat pump; hybrid heat pump systems; cooling capacity; COP, air-source ratio, air-source heat pump*

## 1. Introduction

Energy consumption is growing swiftly with the people's standard of living. The growing demand for renewable energy sources has been driven by the need to reduce greenhouse emissions caused by fossil fuels. Renewable energy technologies research has primarily been focused on solar and wind power because of their ubiquitous and universal applicability [1]. Geothermal energy is also part of renewable energy research and is vitally important for building air-space conditioning. Buildings consume tremendous amounts of energy in a form of heating and cooling. It is estimated that on average a building's energy consumption accounts for 19% of the total social energy consumption [2].

Conventional heating methods based on fossil fuels emit a massive amount of pollutants, consume a large amount of energy, and waste high-grade energy. So, heat pump technology has been gaining attention because of its energy-efficient, environmentally friendly, and cost-effective applications [3]. Among these heat pump technologies include ground source heat pump (GSHP) which typically yields higher heating and cooling coefficients of performance (COP) compared to the water-source heat pump (WSHP) and air-source heat pump systems (ASHP). A heat pump (HP) is a device capable to transfer thermal energy from the outside using the

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refrigeration cycle. Heat pumps inject the heat to the ground (GSHP) or release the heat to the ambient air (ASHP) when cooling a building. The decision on the type of HVAC to use depends on the size, reliability, costs, energy efficiency, and maintenance requirements [4] [5] The heat pump systems that were investigated in this study were the air-source heat pump (ASHP) and hybrid ground-source heat pump (HBHP). In the case of the HBHP, the heat is transferred from the room and deposited underground during cooling, or heat is transferred from the ground to the indoor space during heating. The air-source heat is the same only that the heat is transferred from the outside air to the indoor space for heating or removed from the indoor space to the outdoor air during cooling.

There have been many studies conducted that compare the performance of ASHP to that of GSHP. Urchueguía *et al.* (2008) demonstrated that a ground-coupled heat pump (GCHP) saved about 20% more energy compared to the air-source heat pump [6]. Morrone *et al.* (2014) also showed the economic benefits of using GCHP, particularly in cold climates [7]. Conversely, soil thermal imbalance caused by uneven loads of heating-dominant buildings adversely affects heating capacity and the long-term performance of a GSHP system [8]. This directly affects the initial borehole investment, which hinders the application of GSHP in cold regions.

This work investigates if HBHP is a more energy-efficient and cost-effective option for cooling (or heating) compare to the ASHP. It has been established by many studies that HBHP operates at a relatively higher COP than ASHP resulting in saving on electricity costs and energy consumption. Moreover, this research aims to investigate the role of each component in the overall system COP.

### 1.1. Study location

The ASHP and HBHP performance testing system was conducted using three prefabricated buildings located at Saga University, Saga prefecture in Japan (see Figure 1).



Figure 1: The map of Japan is on the left (a), The red arrow shows the location of Saga Prefecture(b).

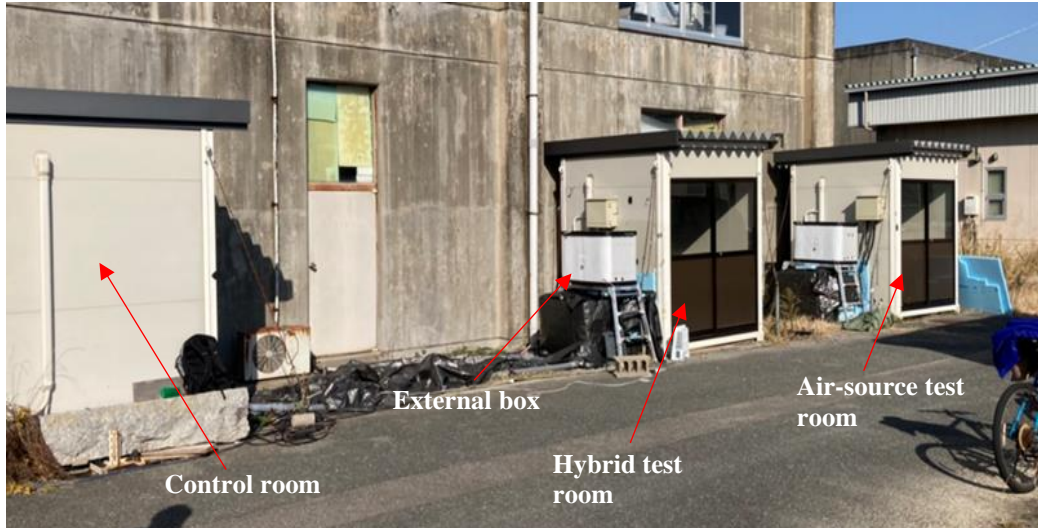


Figure 2: The experimental site for this research.

The control room is on the left, the hybrid test room is in the middle, and the test room for the air-heat source system is on the right. The control room is equipped with a data logger for recording instrument values, a pump for water piping, and a monitor for data observation. The hybrid test room and the Air-source heat pump system test room are each equipped with an indoor unit. In the hybrid heat pump system, the PHE, expansion valve, flow meter, and solenoid valve are installed as a single unit in a box on the side of the prefabricated structure above the outdoor unit (hereinafter referred to as "external box"). Similarly, the expansion valve and flow meter are installed in a box in the air-source heat pump system. The experimental site studied is directed north-south and it receives direct sun radiation from east to west. To avoid heat loss an insulated cover was used (see Figure 3 below).



Figure 3: Insulated experimental room.

## 2. Experimental Device

This section describes the air-source and hybrid heat pump systems in detail. Figures 4 and 5 show the external box for the air-source system and hybrid heat pump system respectively in cooling operation mode.

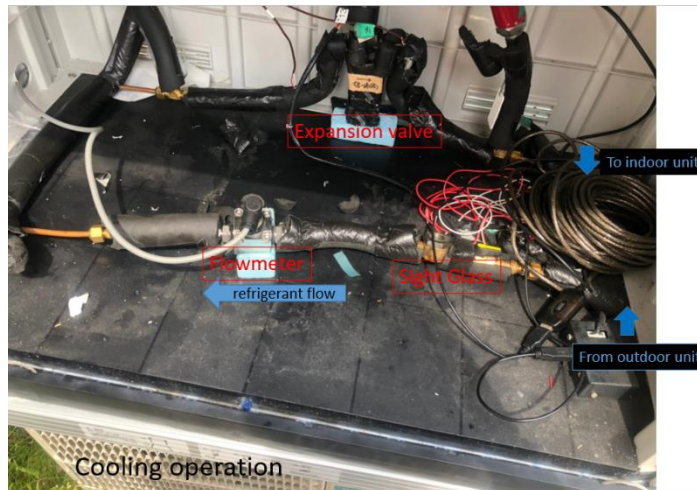


Figure 4: Inside the air-conditioning box for the ASHP system.

The refrigerant used in the refrigeration cycle is R32 (difluoromethane). The refrigerant (R32) becomes a high-pressure gas refrigerant in the compressor and enters the condenser (outdoor unit). In the condenser, the refrigerant condenses from a high-pressure gas refrigerant to a high-pressure liquid refrigerant in order to dissipate heat into the outside air. The refrigerant then enters an expansion valve, where it is expanded to a low-pressure liquid and enters an evaporator (indoor unit). In the evaporator, the refrigerant removes heat from the room, evaporates, and returns to the compressor as a low-pressure gas. In other words, the cycle of compression, condensation, expansion, evaporation, and compression is repeated. The specifications of the components used are described in the table below;

Table 1: Description of the Components of the heat pump.

Component	Type	Operating Principle	Working Fluid	Flow direction
Fan	Propeller	Turbo-type	Gas(R32 refrigerant)	Axial
Expansion Valve	Electronic Expansion Value (EEV)	The EEV controls the precise amount of refrigerant that flows into the evaporator.	Gas(R32 refrigerant)	-
Heat Exchanger	Double U-Tube (30 meters long)	Water moves from the pump to the double U-Tube and to PHE (see <i>Figure 8</i> ).	Water	-

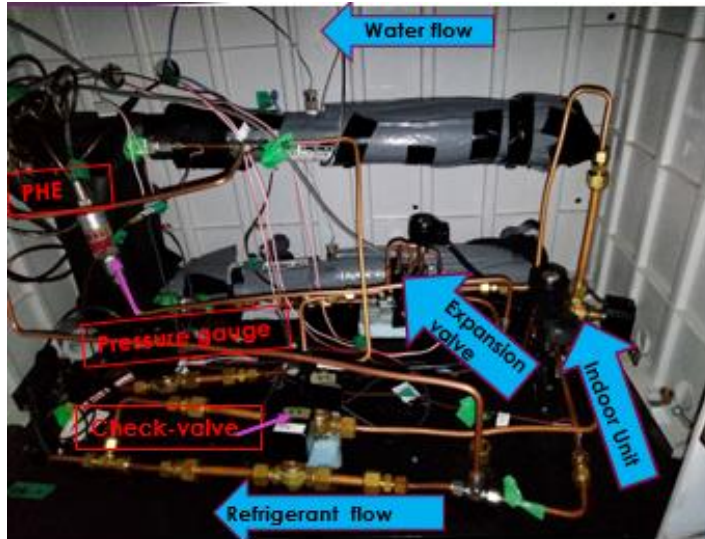


Figure 5: Inside the air-conditioning box for the hybrid heat pump system.

The hybrid heat pump system has a plate heat exchanger (PHE) which is installed in series with the air heat exchanger. The PHE is a heat exchanger between the ground heat source and the refrigerant. The pipes connecting the ground heat exchanger (GHE) and the PHE are filled with water. As in air-source systems, the high-pressure gas refrigerant exiting the compressor enters the condenser (outdoor unit). In a hybrid heat pump system, the refrigerant enters the PHE in a two-phase state, i.e., gas and liquid coexist, after the heat is dissipated to the outside air in the condenser, where it is condensed by dissipating heat to water (underground). In other words, the hybrid heat pump system utilizes both air and water. The high-pressure liquid refrigerant enters the expansion valve, where it is expanded to become a low-pressure liquid, which enters the evaporator, and then the gaseous refrigerant enters the compressor and the cycle repeats again. The measuring instruments for the flow of refrigerant and water are summarized in Table 2 below.

Table 2: Measuring instruments

Instruments	Type of measurement	Accuracy
T-type Thermocouple	Refrigerant temperature	±1°C
K-Type Thermocouple	Water temperature in the GHE	±2.2°C
Pressure Gauge	Refrigerant pressure	±0.25%
Resistance Thermometer	Water temperature	±0.1°C
Volumetric flowmeter	Refrigerant flowrate	±1%
Solenoid Valve	Allow fluid flow in one direction	±2.5%

Table 2 above shows the measuring instruments used to take data in this study. The accuracy of each device was taken from the manufacturer’s websites. The T-type thermocouple and pressure gauge were used to measure temperature and pressure respectively as the refrigerant enters different components in the refrigeration cycle as seen in Figure 6 and Figure 7. The resistance thermometer was used to measure the temperature of water (see Figure 9). The volumetric flowmeter measures the refrigerant’s flow rate. The solenoid valve is an electromechanically controlled valve that is used to regulate the flow direction of the refrigerant.

### 2.1. About the experimental apparatus of the Air-source heat pump system

Figure 6 shows the experimental setup for the Air-source heat pump system. The figure shows the cooling operation. T and P in the figure indicate a thermometer (thermocouple) and a pressure gauge, respectively.

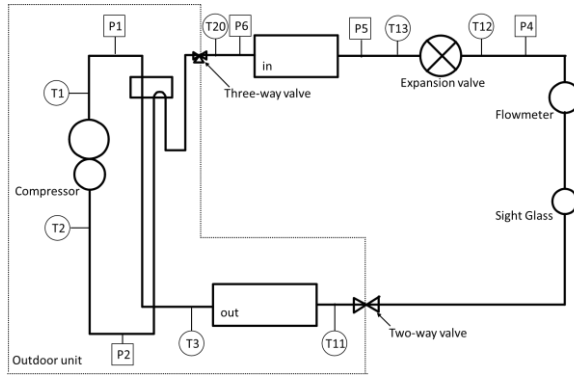


Figure 6: Air-source heat pump system Experimental Schematic.

In Air-source heat pump systems and Hybrid heat pump systems, pressure gauges and T-type thermocouples are installed at the compressor inlet/outlet, heat exchanger inlet/outlet, and expansion valve inlet/outlet. The T-type thermocouple is soldered to the surface of the copper tube. To calculate the mass flow rate of the refrigerant, a volumetric flowmeter is installed at the inlet of the expansion valve. The mass flow rate is obtained by the product of the volume flow rate and the density. Therefore, it is impossible to measure in a two-phase state where the density is not fixed. Therefore, a volumetric flowmeter was installed at the outlet of the condenser (an inlet of the expansion valve) where the liquid condenses to a pure liquid.

## 2.2. About the experimental apparatus of the Hybrid heat pump system

The solid line shows the refrigerant piping and the broken line shows the water piping. The control software for remotely operating the compressor speed, expansion valve opening, outdoor unit fan speed, and indoor unit fan speed is also the same as for the Air-source heat pump system. Five solenoid valves are installed in the hybrid heat pump system.

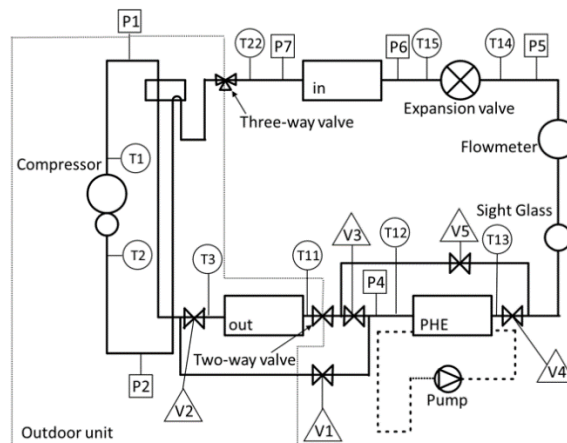


Figure 7: Hybrid heat pump system experimental schematic.

## 2.3. About Water Piping

The water goes from the pump in the control room to the double U-tube for heat exchange with the ground. After leaving the ground heat exchanger (GHE), the water, which is almost equal to the ground temperature, enters the PHE and exchanges heat with the refrigerant.

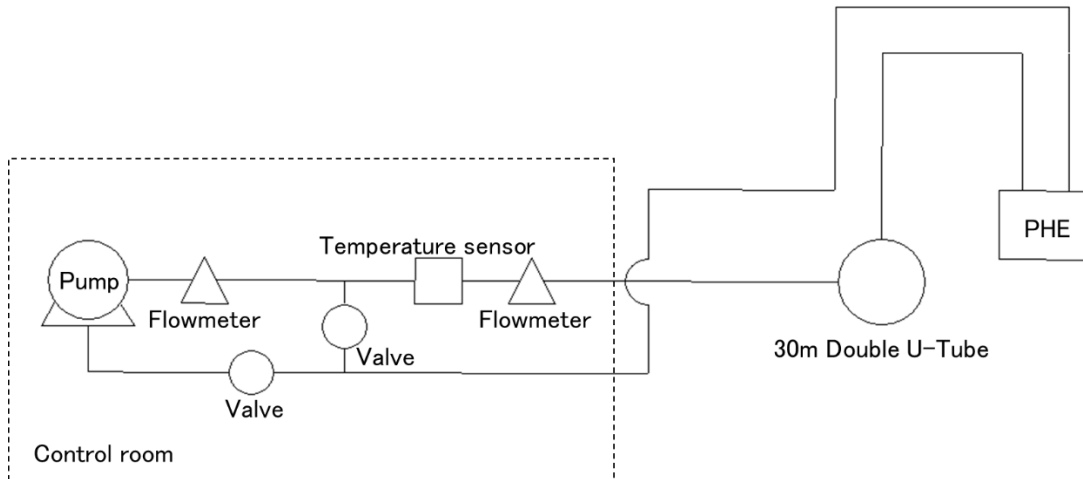


Figure 8: Overall view of water piping.

The two valves in the diagram above regulate the flow rate of water. As the water moves its temperature changes in the circuit. The changes in temperature were measured by the resistance thermometer (Figure 9). The resistance thermometer measures the temperature by utilizing the fact that the electrical resistance of material changes with temperature. Unlike thermocouples, reference contacts are not required, making temperature measurement relatively easy and accurate (see Table 2). However, the temperature range is lower than that of thermocouples.



Figure 9: Resistance thermometer.

The water temperature at the inlet/outlet of the GHE is measured by a K-type thermocouple. The water from the GHE goes to the PHE installed in the external box above the outdoor unit.

### 3. Methodology

#### 3.1. System modeling procedure

The data collected was represented graphically in T-s and P-h diagrams. The system performance was evaluated by the P-h and T-s diagrams. These diagrams monitor the vapor compression refrigeration cycle as it changes states in different components (from the compressor, condenser, metering device, evaporator, and to the compressor again).

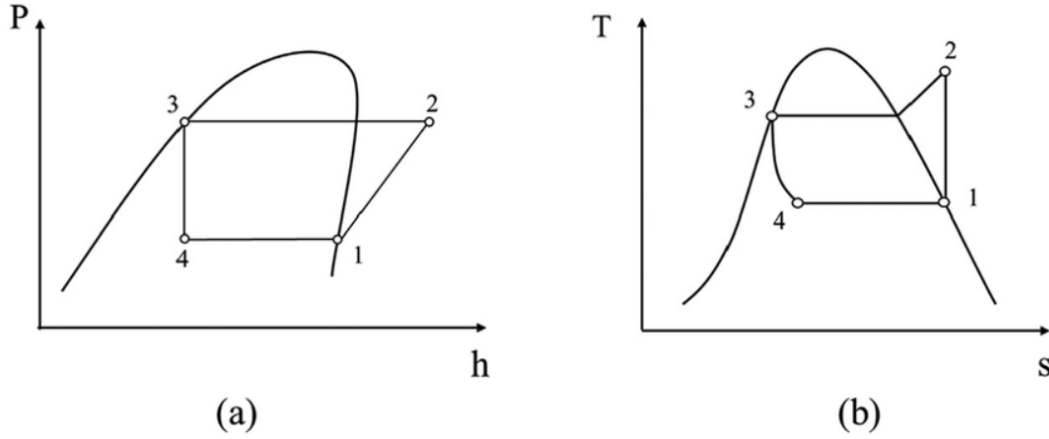


Figure 10: The P-h (a) and T-s diagram (b) [9].

The P-h (a) and T-s (b) diagrams above show the vapor compression refrigerant cycle. The numbers in the diagram indicate the different components which the refrigerant will have to pass through. The movement of the refrigerant through these components will result in a phase change. The refrigerant will move from the compressor (1) after it had been compressed resulting in an increase in its pressure, then it will move to a condenser (2) where the temperature will drop. Position (3) is a metering device (expansion valve) that drops the pressure of the refrigerant as it goes to an evaporator (4) and then it goes to the compressor where the cycle repeats again. The evaporator is where the refrigerant absorbs heat from the room.

### 3.2. Data Reduction

Firstly, hourly dynamic cooling loads for the ASHP and HBHP were calculated using a Visual Basic for Applications (VBA) program in a CSV file. The experimental data were used to calculate COP and evaluate the system performance. The COP is defined as follows:

$$COP_{cooling} = \frac{Q_L}{W_{in}} \quad (1)$$

Where  $Q_L$  is the available heat at the evaporator and  $W_{in}$  is the amount of energy required for compression. Since  $W_{in} = Q_h - Q_L$ , COP could also be expressed as follows:

$$COP_{cooling} = \frac{Q_L}{(Q_h - Q_L)} \quad (2)$$

REFPROP ver. 10 was used to calculate enthalpy and entropy which were automatically plotted in the CSV file. The REFPROP ver. 10 was also used to calculate other important parameters such as the mass flow rate, water mass flow rate, cooling capacity, the amount of GHE, PHE heat exchange rate, pump work, and the COP for both heat pump systems. Out of all the parameters mentioned, the mass flow rate, cooling capacity, and COP were the most important for this research.

The mass flow rate  $\dot{m}_{ref}$  [kg/s] is obtained by the product of the refrigerant volume flow rate  $F_{ref}$  [L/min] and the density  $\rho_{ref}$  [kg/m<sup>3</sup>]. The density of the refrigerant is calculated from the temperature and pressure using REFPROP. The temperature and pressure are referenced to the measured values at the inlet of the expansion valve, which is the location where the flowmeter is installed. The mass flow rate formula is as below:

$$\dot{m}_{ref} = F_{ref} \times \rho_{ref} \times \frac{1}{60} \times \frac{1}{1000} \quad (3)$$

The cooling capacity  $Q_{cooling}$  [kW] indicates the amount of heat the system can remove from the refrigerated space over time. It is obtained by the product of the mass flow rate  $\dot{m}_{ref}$  [kg/s] of the refrigerant and the specific enthalpy difference  $\Delta h_{eva}$  [kJ/kg] of the indoor unit (evaporator for cooling operation).

$$Q_{cooling} = \dot{m}_{ref} \times \Delta h_{eva} \quad (4)$$

Enthalpy is defined as the total heat energy of a system and is equal to the sum of internal energy ( $\Delta U$ ) and the product of pressure ( $P$ ) and volume ( $\Delta V$ ). Mathematically, it can be expressed as,

$$H = \Delta U + P\Delta V \quad (5)$$

The specific enthalpy of the system is defined as the enthalpy per unit mass. It can be expressed as,

$$h = \frac{H}{m},$$

Where  $h$  is the specific enthalpy,  $H$  is the enthalpy of the system and  $m$  is the mass. Thus, the specific enthalpy ( $h$ ) can be defined as the sum of the specific internal energy ( $u$ ) and the product of pressure ( $p$ ) and specific volume ( $v$ ),

$$h = u + pv \quad (6)$$

So, the specific enthalpy difference  $\Delta h_{eva}$  is the enthalpy difference between the inlet and outlet of the evaporator. The evaporator is where the refrigerant absorbs heat from the room in an isobaric heat addition process (see Figure 10). Using thermodynamic principles, the specific enthalpy can be represented as,

$$\Delta h_{eva} = c_p \Delta T \quad (7)$$

Where  $c_p$  is the specific heat capacity at constant pressure, and  $\Delta T$  is the temperature difference between the inlet and outlet of the evaporator.

Coefficient of performance commonly known as COP is a measurement of the energy efficiency of a system's heating or cooling performance. The COP was used to evaluate the performance of an air-conditioner. It is obtained by the quotient of the air-conditioner's power input  $W_{HP}$  [kW] to the amount of cooled heat  $Q_{cooling}$  [kW]. The  $COP_{AIR}$  [-] for the air-heat source system is shown in the formula below:

$$COP_{AIR} = \frac{Q_{cooling}}{W_{HP}} \quad (8)$$

The hybrid heat pump system can be obtained by considering, the pump power  $W_{pump}$  [kW].  $COP_{HB}$  [-] of the hybrid heat pump system is shown in the Equation below:

$$COP_{HP} = \frac{Q_{cooling}}{W_{HP} + W_{pump}} \quad (9)$$

### 3.3. Data Acquisition

The cooling data was collected from the beginning of August to the first week of October. It was taken in four stages. The data were collected in four stages for both ASHP and HBHP. The data collection steps are summarized below:

- Controlling the compressor speed, expansion valve opening, and outdoor fan in an uninsulated room.
- Automatic air-conditioning ("free mode") operation in an uninsulated room.
- Controlling the compressor speed, expansion valve opening, and outdoor fan in an insulated room.
- Automatic air-conditioning ("free mode") operation in an insulated room.

In the first stage; data was collected by controlling the compressor speed, outdoor fan speed, expansion valve, indoor temperature, and PHE. This data was collected to optimize the whole system's performance by getting desirable values for the COP, cooling capacity, superheat, and air-source percentage ratio (for the hybrid heat pump system). The second stage was collecting data by letting the air-conditioning operate freely as in any building. The changes in a compressor, outdoor fan speed, and expansion valve over time were recorded in a

CSV file. Over time, the COP, cooling capacity, and indoor temperature variations were also noted. The third stage involved covering the two experimental rooms with an insulated cover to reduce heat from escaping easily. This was done to mimic how buildings are normally constructed. Buildings in regions with extreme weather like in Japan are built with indoor insulation, so heat doesn't escape easily unless an air-conditioner is used. This stage was performed exactly like in stage one where we controlled for different system components and observed their influence on the COP, cooling, superheat, or air-source percentage ratio (for the HBHP system). The final stage was the "free mode" where we allow the air-conditioner to run without any interference and changes for compressor speed, outdoor fan speed, and expansion valve were recorded in a CSV file. The air-source percentage ratio was also recorded for the HBHP system. The formula for the air-source percentage ratio is defined below:

$$\text{ASR} = \frac{\Delta h_{\text{Air}}}{(\Delta h_{\text{Air}} + \Delta h_{\text{PHE}})} \quad (9)$$

The reason for calculating the ASR for the HB system was to correlate the percentage of air with COP and cooling capacity. This correlation will help us optimize for the correct amount of air-source heat required in the HBHP system to improve the COP and cooling capacity.

## 4. Results and Discussion

The results focus mainly on comparing the performance (COP), ground heat exchange percentage, cooling capacity, inlet condenser temperature, and percentage of improvement comparison of the two systems.

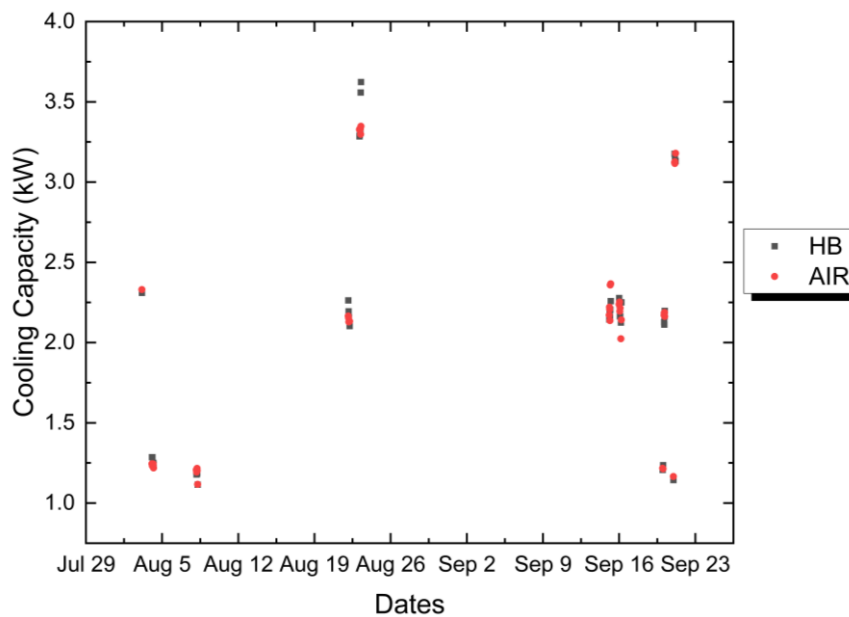


Figure 11: Cooling capacity for different days.

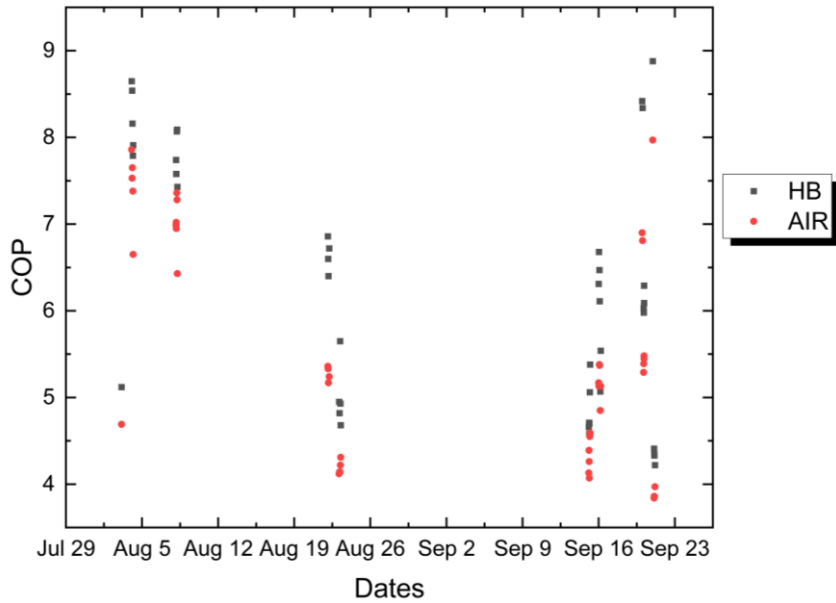


Figure 12: Coefficient of performance for different days.

The two figures above (Figure 11 and Figure 12) compare the hybrid and air source systems. HB stands for the hybrid heat pump system and AIR is for the air-source heat pump system. Figure 11 shows the cooling capacity comparison between HBHP and ASHP for different numbers of days. The HB shows similar cooling capacities for specific days because we controlled each system's specific cooling capacity range. Figure 12 depicts the COP comparison between the two systems. HBHP shows a greater performance overall as compared to the ASHP system.

Table 3: Hybrid and Air source performance comparison data.

Cooling capacity	HB		AIR		Percentage Improvement (%)
	COP	Outdoor Inlet Temperature (°C)	COP	Outdoor Inlet Temperature (°C)	
1kW	8.07	30.77	7.36	30.76	9.65
	8.09	31.16	7.28	31.33	11.13
	7.43	31.3	6.99	31.48	6.29
	7.58	32.5	6.95	31.92	9.06
	7.58	32.94	7.02	32.3	7.98
2.2kW	6.72	30.42	5.24	30.57	28.24
	6.6	32.07	5.33	31.64	23.83
	6.86	32.18	5.36	31.47	27.99
	6.4	33.56	5.17	32.56	23.79
	5.12	34.47	4.69	33.98	9.17
3.3kW	4.68	29.36	4.31	29.5	8.58
	4.93	29.87	4.22	29.91	16.82
	5.65	30.51	4.14	30.85	36.47
	4.82	30.8	4.14	30.99	16.43
	4.95	31.59	4.12	31.17	20.15

Table 3 above shows comparison data for the hybrid and air-source systems. Cooling capacity was controlled to a specific range to monitor the COP and outdoor inlet temperature for both systems. The significant metric of comparison is displayed in the last column where a hybrid percentage improvement is shown relative to the air. Higher cooling capacities display a high percentage improvement. A system that is able to remove heat efficiently will have a higher performance improvement. The reason that the hybrid heat pump system shows a higher performance improvement is that it cools the refrigerant coming from a compressor using two main components. The first component is the outdoor unit (condenser) and the second component is the plate heat exchange (PHE) which reduces the refrigerant temperature using the water cycle (See Figure 7 to see the refrigerant and water circuit).

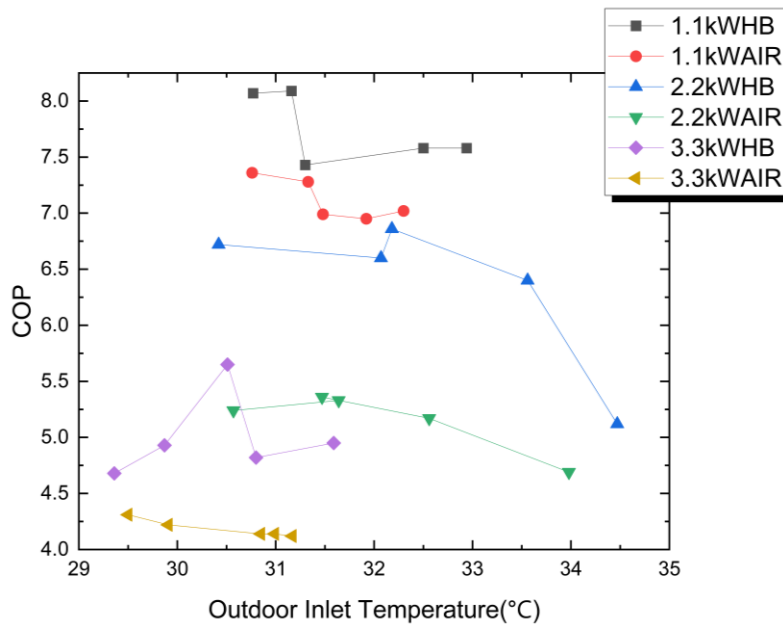


Figure 13: COP comparison against outdoor unit inlet temperature for different cooling capacities.

Figure 13 above depicts the relationship between COP and the outdoor unit inlet temperature for both systems. The COP for both systems dips slightly as the outdoor inlet temperature increases. Increasing the temperature of the gas requires an increase in work output to condense the refrigerant. So, for the same work output, the temperature of the stream leaving the condenser increases for a fixed input temperature to the condenser, and the heat rejection capacity of the condenser decreases. Thus, the COP for both systems decreased slightly. The hybrid heat pump system shows a higher COP compare to the air-source system in each cooling capacity range.

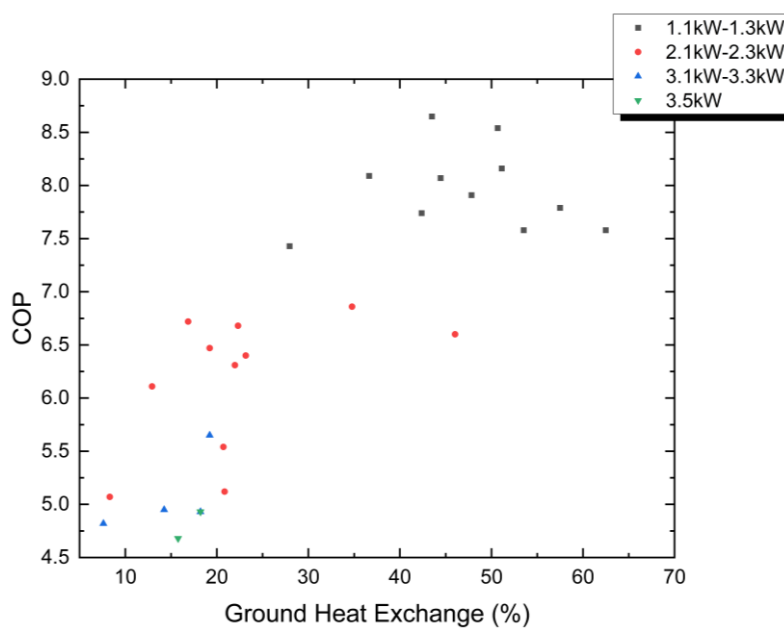


Figure 14: COP comparison against ground heat exchange percentage for different cooling capacities.

The hybrid heat pump system has an additional water circuit that exchanges heat with the refrigerant using the PHE. PHE is the main component in our circuit responsible for the improvement of a hybrid heat pump system compared to an air-source system. The ground source heat percentage was also measured to understand the role of the PHE in improving performance. Figure 14 above shows the relationship between the ground heat exchange percentage and the COP for each specific cooling capacity range. Figure 14 can also be correlated to the air-source ratio which demonstrated the percentage of air in the hybrid heat pump system required for optimum performance. Then, the graph shows that increasing the percentage of ground source heat improves the COP. Varying values of ground heat exchange percentage parameters were obtained by changing the compressor speed, outdoor fan speed, and PHE control valve.

Table 4: The summary table for the COP of the two systems.

Cooling Capacity	Average COP		COP <sub>improv</sub> % (HB vs AIR)
	HB	AIR	
1.1kW	8.08	7.20	10.91
2.1kW	5.78	4.97	13.41
3.1kW	4.70	4.05	13.43

Table 4 shows the COP comparison between HB and AIR source systems. These are average COP values for each cooling capacity range. The HB performed better in every measurement taken for the COP. The highest disparity between the two systems is at higher cooling capacities. This means that hybrid heat pump systems perform better in regions or buildings that require a lot of energy consumption as a requirement to meet air-conditioning needs. The COP percentage comparison was calculated as follows:

$$COP_{improv} = \left( \frac{COP_{ave\_HP} - COP_{ave\_AIR}}{COP_{ave\_HP}} \right) \times 100$$

Where,

$COP_{improv}$  is the COP percentage improvement of HB against AIR source system,  $COP_{ave\_HP}$  and  $COP_{ave\_AIR}$  is the average coefficient of performance for a specified cooling capacity range for the hybrid and air-source system respectively.

## 5. Conclusion

In this research, a performance comparison between the hybrid and air-source heat pump systems was experimentally investigated. The findings obtained in this research are as follows:

- As a result of the experiment, the hybrid heat pump system's coefficient of performance (COP) is higher than the air-source system. The average COP for the 3.1kW cooling capacity showed the highest COP improvement between the two systems. The Average COP obtained for the HB and AIR was 4.70 and 4.05 respectively. Thus, this resulted in the HBHP performing 13.43% better than the ASHP.
- An increase in outdoor inlet temperature decreased the COP in both systems. This results from the condenser's inability to reject more heat without affecting the performance of the system. This can be attributed to the higher energy demand by the system to meet the higher cooling requirement.
- The cooling capacity ranges obtained by controlling the compressor speed, expansion valve opening, and outdoor fan speed showed COP values for the two systems that are comparable to other authors. Further research will be focused on system performance comparison for the heating operations. Thereafter, an in-depth component (compressor, condenser, expansion valve, evaporator, and PHE) impact on the overall performance will be fully assessed.

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