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Potential for Electrical Energy Savings in AC Systems by Utilizing Exhaust Heat from Outdoor Unit

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Abstract

This study explores the potential of utilizing waste heat from air conditioning systems, one of the largest consumers of electrical energy. Currently, most of the waste heat generated by outdoor units is typically released into the environment without being utilized, leading to missed energy-saving opportunities. This study analyzes the potential for improving electrical energy efficiency in air conditioning (AC) systems by harnessing this waste heat. Two primary approaches are evaluated: the first is the use of waste heat for domestic water heating, and the second is the conversion of heat into electrical energy using thermoelectric generators (TEG). The results of this research indicate that both methods have the potential to improve overall energy efficiency significantly. However, challenges related to conversion efficiency and integration of these technologies with AC systems require further, more specific studies. These findings are expected to contribute to more efficient and environmentally friendly cooling systems by optimizing technology and overcoming barriers to wider implementation.

1. Introduction

Air conditioning systems consume a large amount of electricity, whether in residential, commercial, or industrial, increasing operational costs and significantly impacting global warming through greenhouse gas emissions and national energy security [1–3]. One aspect often overlooked is the waste heat generated by the outdoor unit of the air conditioner, which is generally released directly into the environment without being utilized, thus potentially becoming wasted energy [4–6].

Improve the energy efficiency of the air conditioning system by utilizing more environmentally friendly technology [7]. Using waste heat from outdoor units can provide dual benefits, reducing energy requirements and opening up opportunities for additional energy applications, such as domestic water heating, dry room, or energy conversion. In addition, one of the potential technologies is thermoelectric technology, which can convert temperature differences into electrical energy. In the outdoor unit of an air conditioner, heat is generated as a by-product of the cooling process [8–10]. This heat is often released into the environment without being utilized. However, with the right technology, such as thermoelectric generators (TEG) or heat exchangers, thus heat can be converted into electrical energy. More efficient and environmentally friendly air conditioning systems can be developed to reduce carbon emissions

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Table 1. Specification material unit

Outdoor type U-12ME2H7	Specification
Power supply	3ø, 380V, 50 Hz
Capacity	33.5 kW 114,300 BTU/h
Current	11.8 A
Input power	7.08 kW
EER	4.73
Max. Working pressure (bar)	High sidebar: 38 Low sidebar: 31.1

and support global sustainability targets and climate change mitigation [11–14].

Various studies have explored waste heat utilization to improve energy efficiency and provide optimal design suggestions. For instance, Yaakop et al. [15] operated HVAC systems using the refrigerant cycle, where the condensing unit releases heat into the surrounding air, which can then be utilized for drying. Oluleye et al. [16] focused on waste heat utilization for fossil fuel conservation, particularly reviewing cutting-edge technologies like the Organic Rankine Cycle (ORC) to harness waste heat. Kang et al. [17] proposed a ranking system to evaluate energy recovery from waste heat, considering factors like energy performance, greenhouse gas reduction potential, and economic viability.

Building on these concepts, He & Lin [18] presented a novel natural gas liquefaction system that integrates waste heat from gas turbine exhaust to lower energy consumption. Similarly, Li et al. [19] suggested a new cascade heating system to recycle steam exhaust from turbine units in air-cooled power plants for clean urban heating. Wahlroos et al. [6] investigated the potential of utilizing waste heat from data centers in Nordic countries, highlighting challenges such as a lack of transparency between district heating operators and data center operators while assessing the economic and environmental impact.

Further studies, such as Su et al. [20], explored waste heat utilization in various industries, classifying technologies based on their thermal performance, economic benefits, and environmental impacts. Haywood et al. [21] examined renewable energy sources for cooling data centers, focusing on utilizing exhaust heat and implementing new methods like mineral oils for better energy management.

Research into air conditioning systems also reflects the growing interest in waste heat recovery. Setyawan [22] analyzed the impact of airflow resistance on the performance of air conditioning systems, while Poojeera et al. [23] investigated the efficiency of combined air conditioning and thermoelectric cooling systems. AlQdah et al. [24] examined automotive AC systems that use diesel engine exhaust for heat generation, optimizing thermoelectric air conditioning (TEAC) systems. Meanwhile, Rongdi et al. [25] highlighted the advantages of heat pump AC systems over traditional units, showcasing higher efficiency and waste heat recovery.

Advancing these ideas, Attar [26] advanced thermoelectric air conditioners (TEACs) for vehicles by testing innovative designs in real-world conditions, while Liu et al. [27] introduced a refrigerant-free geothermal TEAC system for higher efficiency. Further optimization of TEAC systems was conducted by Attar et al. [28], using thermoelectric materials to enhance cooling performance. Similarly, Dizaji et al. [29] researched commercial thermoelectric modules, achieving improved cooling properties and performance. Wiriyasart et al. [30] developed a thermoelectric air conditioning prototype, validating their theoretical results through experimental testing.

Previous studies show that waste heat from outdoor air conditioner units has been widely utilized [15]. However, AC technology continues to evolve, leveraging advanced technologies to achieve maximum efficiency [31, 32]. For this reason, we focus on analyzing the performance of outdoor units with inverter compressors under relatively higher temperature conditions. This analysis requires support from key parameters, such as the temperature difference between the gas and liquid phases. Here, we explore the potential of utilizing waste heat from AC outdoor units. This study's specific contribution is identifying how variations in condenser temperature, pressure, and ampere in inverter compressors can enhance thermal efficiency and significantly reduce electrical energy consumption.

2. Materials and Methods

The components and performance characteristics of the outdoor unit play a critical role in determining overall efficiency and potential energy savings. Table 1 provides the detailed material specifications for the outdoor unit used in this experiment. The experiment utilized an outdoor model U-12ME2H7, equipped with a rotary inverter compressor technology, consuming up to 7000 watts, powered by a 3-phase source, with a cooling capacity of 33.5 kW, and using refrigerant type R410A. This configuration presents a significant opportunity to enhance the unit's efficiency.

There are standards and installation procedures that need to be considered. Figure 1 shows the AC

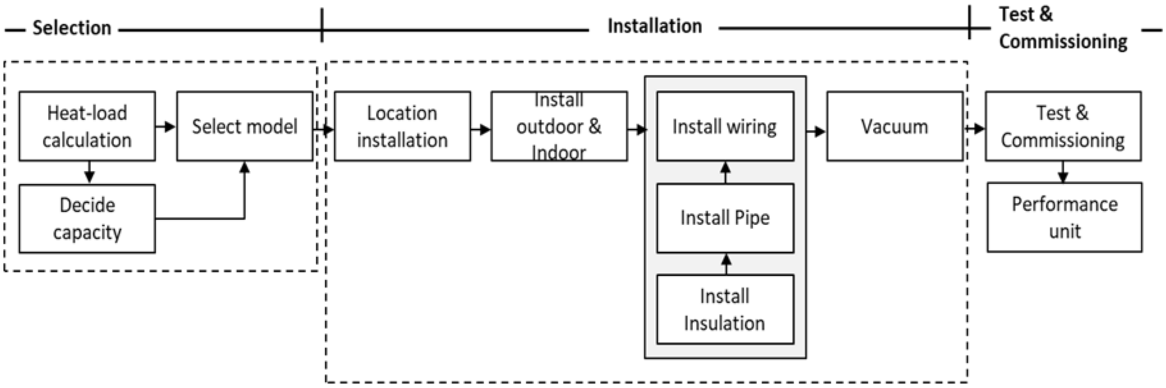


Figure 1. Installation process air conditioner.

unit installation process. At this stage, installing the unit will focus on identifying the available potential and calculating the cooling requirements based on the intended use. The placement of the indoor and outdoor units, piping, wiring, and electrical systems follows this. These steps must adhere to standards to achieve optimal results. Once all components are correctly positioned, data on system performance measurements are collected. The accuracy in selecting the cooling requirements and the capacity of the cooling unit will determine both performance and efficiency [33]. An analysis of the available heat sources is necessary to harness the potential of waste heat from cooling systems. Identifying the waste heat sources will facilitate its utilization; in this case, an analysis is required to assess the available potential [34].

The calculation for the potential waste heat generated from the air conditioning compressor, with Q_{ex} is as shown in Equation 1:

$$Q_{ex} = m_a c_{p,a} \Delta T \qquad (1)$$

Where; m_a [kg/s] is the mass flow rate of air, $c_{p,a}$ [J/kg°C] is the specific heat capacity of air and ΔT is the temperature difference between the hot air T_e [°C]. Temperature sensors are placed on the compressor, at the outdoor unit fan outlet, and in the surrounding air to collect data. A control panel records this data for further analysis [35, 36]. To observe the potential of waste heat, some key factors need to be considered, such as ambient temperature, compressor temperature, and the temperature change of the gas in the condenser [37]. These factors are critical for ensuring that optimizing waste energy utilization aligns with the refrigeration process [31].

For an outdoor system wiring diagram, it is important to understand the role of each of the main components in the refrigerant cycle**.** Figure 2 shows the outdoor variable refrigerant flow (VRF) wiring diagram. The compressor is the main component responsible for compressing the refrigerant, increasing its pressure and temperature before entering the heat exchanger. The gas heat exchanger functions as a component that exchanges heat between the refrigerant and the surrounding environment, typically aided by a fan to facilitate temperature exchange. This process lowers the gas temperature to a liquid refrigerant exchange. This process lowers the gas temperature to a liquid refrigerant phase. The temperature difference between the heat exchanger gas (H/E.G) and the heat exchanger liquid (H/E.L) can be observed. The capillary tube is an expansion device that regulates the refrigerant flow from the condenser to the evaporator [38]. By understanding the function of each component, temperature measurements can be obtained to analyze waste heat in the vapor compression system [39].

Examine the outdoor wiring diagram; there is some potential for utilizing waste heat from the unit**.** Figure 3 shows the potential concept of outdoor waste heat utilization. The design concept is to harness the heat the outdoor air conditioning unit produces. As shown, the waste heat from the compression of high-pressure and high-temperature refrigerant gas is then directed to a condenser equipped with fins to increase the surface area for heat dissipation. At this stage, the high-temperature gas passes through the condenser, releasing the heat absorbed from the indoor evaporator [38]. The outdoor unit also has a fan to accelerate heat dissipation by blowing it into the surrounding air. As the heat is released into the surrounding air, the refrigerant gas transitions from a gas to a high-pressure liquid phase [40].

The effect of heat temperature on the system can be observed in the experimental configuration of the outdoor system shown in Figure 4. The measurement of compressor temperature data is obtained using a temperature sensor to determine the temperature generated during the refrigerant compression [41].

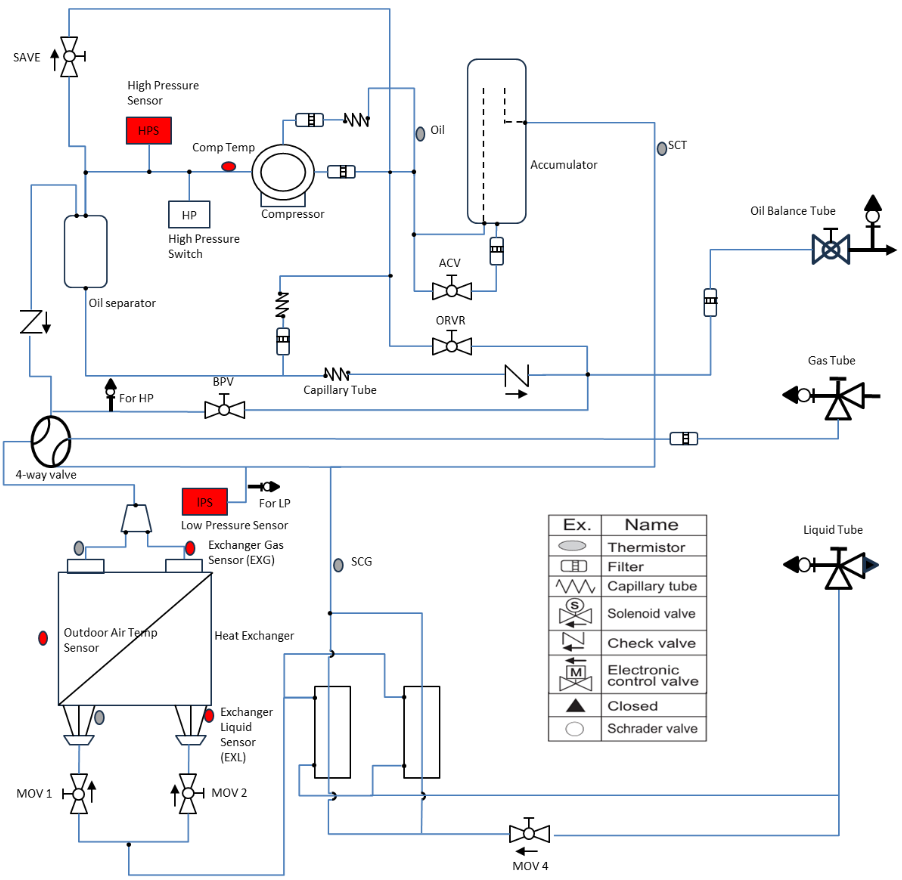


Figure 2. Diagram wiring outdoor variable refrigerant flow (VRF**).**

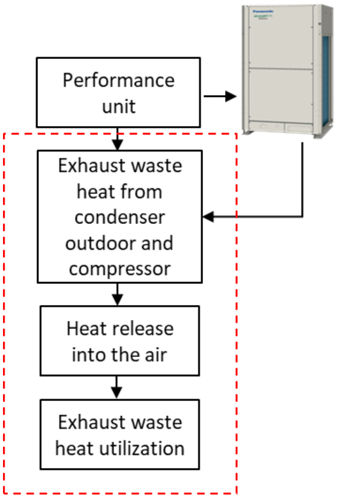


Figure 3. Concept of utilizing potential heat dissipation.

Additionally, the current and voltage flowing through the compressor are measured to observe the ampere conditions on the rotary inverter compressor. A High-Pressure Sensor (HPS) is placed on the compressor discharge pipe to monitor the refrigerant's HPS condition.

Once the refrigerant is compressed at high pressure and temperature, it is directed to the condenser. A temperature sensor (H/E.G) is installed to monitor the temperature of the refrigerant entering the condenser in a high-temperature gaseous state. Within the condenser, the refrigerant's temperature is reduced, causing it to change into a mixture of gas and liquid. At the end of the condenser pipe, another temperature sensor (H/E.L) is installed to track the refrigerant's temperature condition. To assess the impact of surrounding temperature, an ambient temperature sensor (TO) is also placed to determine its effect on H/E.G, H/E.L, compressor temperature, ampere readings, and the overall performance of the system.

After passing through the motorized valve (MOV), the refrigerant becomes low-pressure and takes on a liquid form before being directed to the evaporator. The evaporator absorbs heat from the surroundings, causing the refrigerant to change from liquid to gas as it returns to the compressor. A Low-Pressure Sensor (LPS) measures the refrigerant's low-pressure condition as it returns to the compressor [42, 43]. The target temperature for data collection is set to 24 °C on the remote control.

The main board system controls all sensor data, and the desired information is obtained using a separate tool-checker software. This data is converted into an application that can be monitored and recorded on a computer, allowing for the acquisition of the necessary

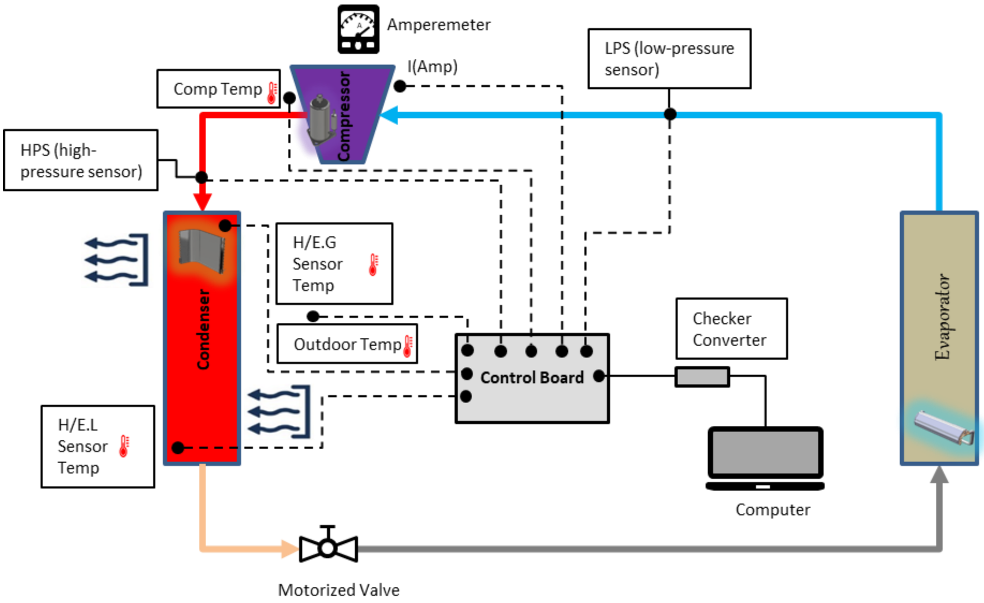


Figure 4. Experimental setup.

information. The recorded temperature data will then be analyzed to assess the potential heat that can be harnessed for further utilization [44].

3. Results and Discussion

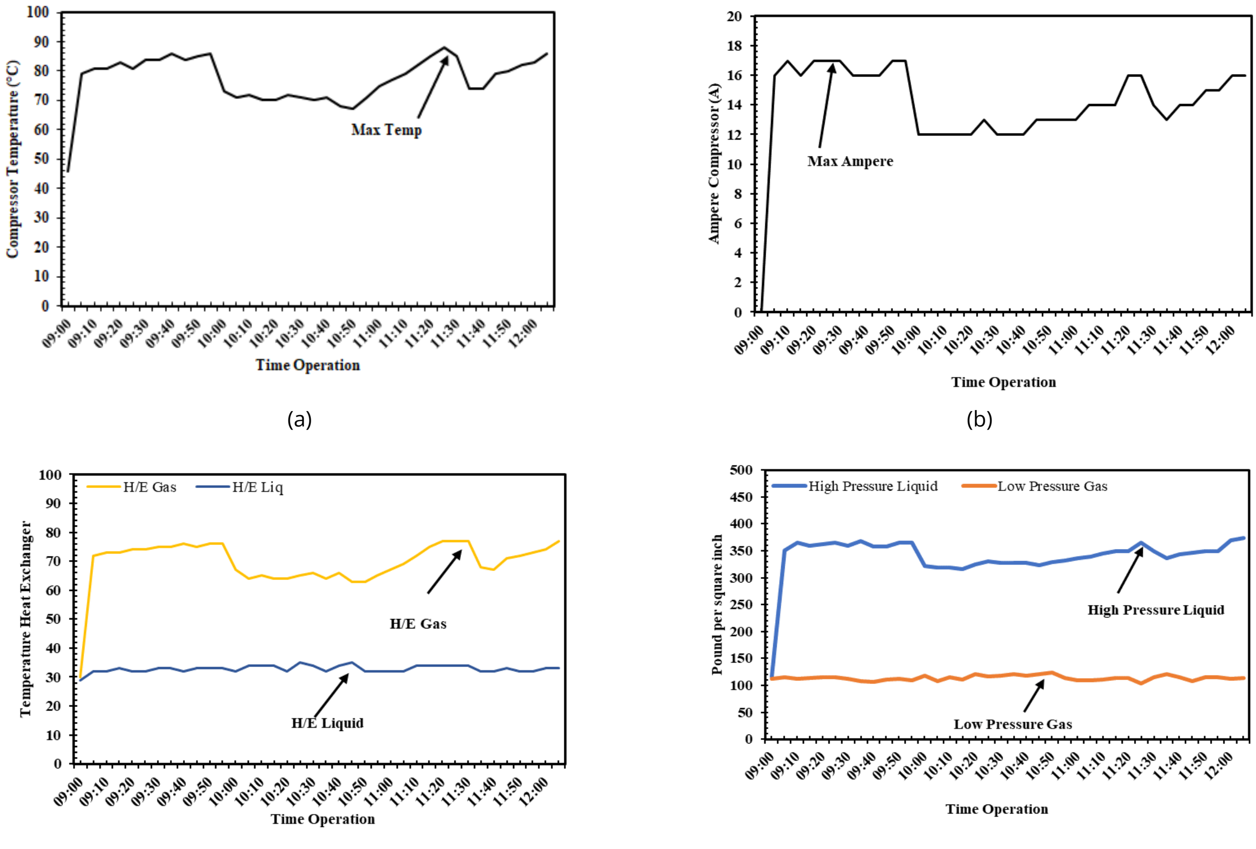
To visualize the performance of the main parameters during operation, we present data on the temperature and current variations of the main components of the AC system (Figure 5). The first aspect, compressor temperature (Figure 5a), explains the variations of the inverter compressor during operation from 09:00 to 12:00. At the beginning of the operation, the compressor temperature rose sharply, reaching 70 °C in less than 30 minutes. After this initial spike, the compressor temperature stabilized in the range of 70 °C to 80 °C until around 10:30. However, significant fluctuations were observed after 11:00, with the temperature peaking at approximately 90 °C by 11:30. Following this peak, the compressor temperature decreased and stabilized again at around 85 °C toward the end of the operation.

The compressor current (Figure 5b) also demonstrated notable trends, rising sharply at the beginning of the operation and reaching a maximum value of around 16 A at 09:30. There were subsequent drops in current, fluctuating around 12 A at several points. Nevertheless, the current gradually increased again around 11:30 before experiencing slight fluctuations and stabilizing at approximately 15 A by noon.

For the heat exchanger temperature (Figure 5c), the EXG temperature is represented by a yellow line and is significantly higher than the H/E.L temperature, as shown in a blue line. At the start of the operation, the gas heat exchanger temperature increased sharply, reaching about 80 °C before decreasing after 10:00. By 11:30, the H/E.G temperature rose again, nearing 90 °C, before dropping at the end of the observation period. In contrast, the H/E.L temperature remained more stable throughout the operation, fluctuating between 40 °C and 50 °C, though the variations were not as pronounced as those of H/E.G.

Lastly, the high liquid and low gas refrigerant pressure (Figure 5d) exhibited significant trends. The high pressure increased sharply after the compressor became active, peaking at around 368 psi at 09:30. It then remained relatively stable, ranging between 300 and 350 psi, with further fluctuations toward the end at noon. Meanwhile, the low pressure peaked at around 88 psi at 09:30 and stabilized between 60 and 80 psi. This analysis shows that the interaction between the compressor temperature, electrical current, condenser heat exchanger, and refrigerant pressure significantly influences the performance of inverter air conditioning systems [45, 46]. Understanding these variables can help improve energy efficiency and overall system performance.

To ensure optimal performance, several critical stages are involved in the installation process of the air conditioning flow process for waste heat utilization, as shown in Figure 6. Before the unit is installed, an important aspect to be considered is the waste heat from the outdoor unit. If left unused, this waste heat can be wasted on the environment. Still, with an approach to utilizing waste heat, the energy can be recovered to improve the overall system efficiency [6]. In the first



(a) (b)

(c) (d)

Figure 5. Parameter analysis performance: (a) Compressor temperature, (b) compressor current, (c) heat exchanger temperature, (d) High liquid pressure and low gas refrigerant pressure.

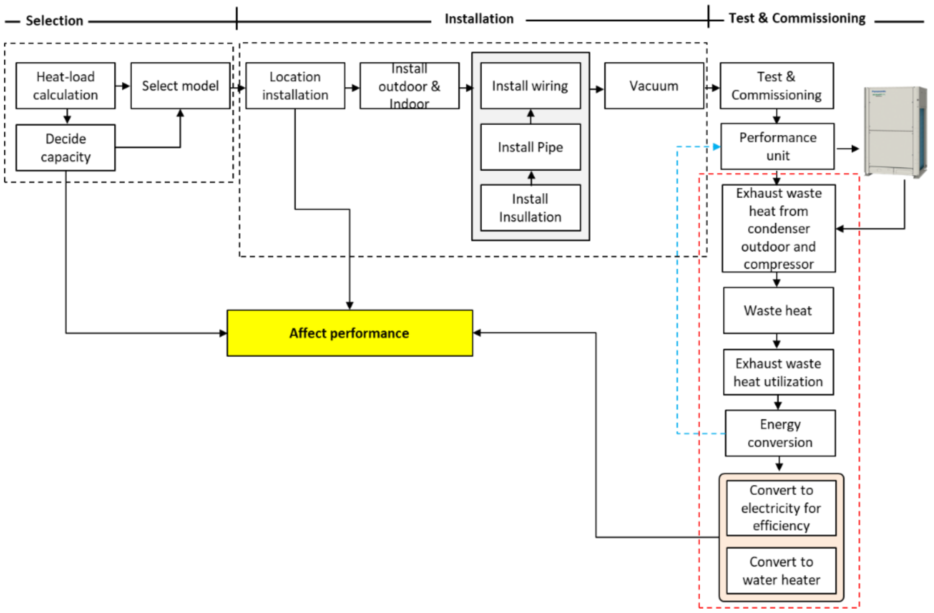


Figure 6. Flow process for utilizing heat exhaust in air conditioner machines.

stage, the heat expelled from the condenser and compressor can be captured and redirected as useful energy, such as electricity conversion or water heating. Converting waste heat into electricity provides energy efficiency benefits to the system, where it can be used to drive the fan as an additional source to remove heat from the condenser, making it more efficient. Another alternative is to convert the waste heat into hot water, which can be used for household needs, supplying hot water, thus achieving efficiency and offering a solution for utilizing wasted energy [31].

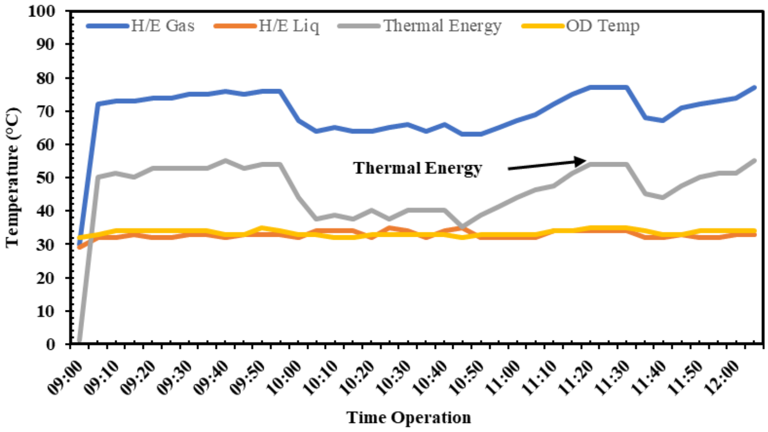


Figure 7. Condenser temperature and thermal energy.

The potential thermal energy on condenser temperature is shown in Figure 7. This figure shows the relationship between the temperature of the H/E gas in the condenser and the thermal energy. The left Y-axis represents the condenser gas temperature values. In contrast, the right Y-axis (thermal energy in kJ) represents the thermal energy calculated from the compressor gas, and the X-axis shows the data collection period over 3 hours. The condenser gas temperature fluctuation starts rising at approximately 70 °C at 09:00, followed by slight fluctuations. However, this temperature generally remains stable at 70 °C to 80 °C. The thermal energy line illustrates the fluctuation in thermal energy produced based on changes in the condenser gas temperature. The thermal energy produced from 0.3 kg water at approximately 4o kJ fluctuates throughout the measurement period, following a pattern corresponding to gas temperature changes but at lower values.

Figure 8 shows waste heat utilization for water heating and electricity generation to improve performance efficiency. Utilizing waste heat for water heating and electricity generation enhances system performance efficiency. The heat produced by the condenser and compressor, often underutilized, can reach temperatures between 40 °C and 80 °C. This waste heat has considerable potential and can be optimized by directing it through heat exchanger pipes connected to a water heating tank. This process enables the water in the tank to reach temperatures sufficient for various household needs, reducing dependence on conventional water heaters powered by electricity or fossil fuels. In addition to heating water, part of the waste heat can be converted into electricity using thermoelectric generator (TEG) modules. At exhaust temperatures between 40 °C and 60 °C, the TEG module utilizes the temperature difference between the hot side of the exhaust pipe and the cool side exposed to the ambient air. Through the Seebeck effect, the module generates an electric current that can be used for energy efficiency in the refrigeration process [42, 45–47].

The results regarding the compressor current, compressor temperature, condenser, and pressure show significant potential for harnessing the available exhaust heat. From the reduction analysis, three key areas emerge that require further discussion:

First; issues related to further technical improvements for greater energy savings. This can be achieved by modifying methods through process reengineering and technological innovations, such as integrating waste heat utilization for household water heating and thermoelectric systems. This would enhance the performance of air conditioning (AC) units by reducing the electrical load on the system. To achieve optimal results, several steps are necessary, including modifying the heat exchanger gas pipe to the water heating tank and conducting precise calculations in line with thermodynamic properties. The goal is to ensure that the relationship between heat, energy, and work operates efficiently based on vapor compression [48, 49].

Second; ensuring that the potential for waste heat utilization does not interfere with the cooling unit’s performance. To ensure that the energy from the vapor compression machine can be optimally utilized in the long term, proper planning from the start is required, including selection the right unit, capacity, intended use, cooling targets, and placement location.

These factors must be carefully calculated to optimize cooling processes, utility, and energy. Furthermore, proper maintenance must be conducted to ensure the compressor operates efficiently. Attention to these aspects is crucial to making the energy consumption of each process more efficient [47, 50].

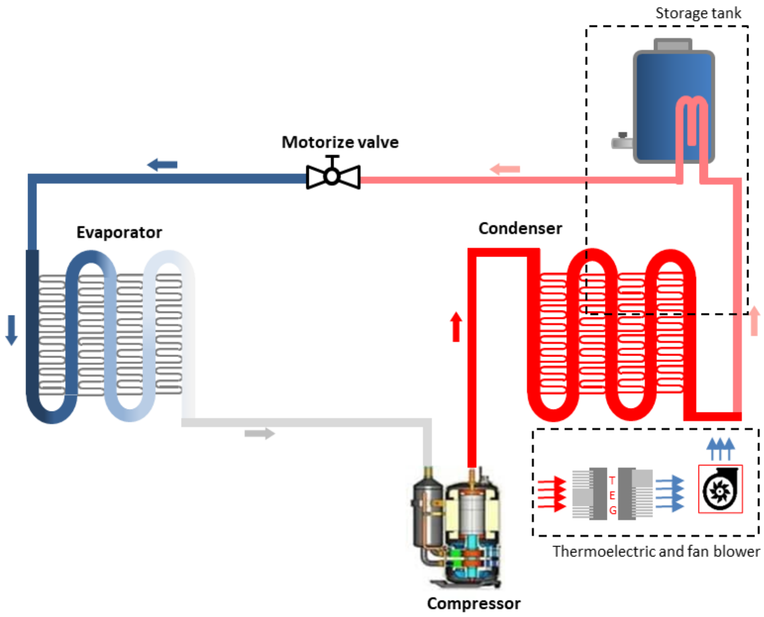


Figure 8. Potential utilization of waste heat.

Third; to achieve the goals of energy utilization, regular checks must be conducted to ensure the process runs smoothly, including outdoor and indoor unit maintenance and performance data logging such as pressure, current, and temperature. Continuous improvement processes should be implemented to ensure better conversion efficiency, supported by energy management control systems [51].

Finally, there is a potential application in utilizing the waste heat from outdoor units' AC systems by employing a heat recovery system, where the waste heat is used to heat water or air for the dryer room, thus improving efficiency. Additionally, integrating the system with thermoelectric generators can achieve a more efficient outcome, leading to a more environmentally friendly solution. Several limitations need to be considered. First, the effectiveness of this system heavily depends on environmental conditions, such as outdoor temperature and cooling load, which can influence the amount of waste heat available for recovery. Second, the heat exchange efficiency between the gas heat exchanger and water also highly depends on the optimal design and material selection, which requires further research. Finally, implementing this system may not be fully compatible with all types of air conditioners, and significant modifications to existing AC systems may be required, potentially increasing the installation cost and complexity. This system can significantly contribute to determining the efficiency of the heat exchange process between the gas heat exchanger and water, where the energy efficiency ratio becomes a reference in energy utilization. For future research, it is possible to develop and optimize the heat recovery system to utilize the waste heat from the condenser effectively. This includes analyzing the ideal material for the heat exchanger, system design, and heat conversion efficiency into usable energy.

4. Conclusions

This study demonstrated that utilizing waste heat from AC units effectively saves electrical energy and improves overall system efficiency. The application of these findings is highly relevant in the HVAC industry and residential sectors, where implementing such systems can reduce operational costs and energy burdens. The primary contribution of this research is the development of waste heat utilization strategies that can be integrated into existing AC systems to enhance energy efficiency. For future research, it is recommended that various climate conditions and surrounding environments be investigated further, as well as different types of AC units, and the technology be tested on a large scale. Additionally, exploring the combination of waste heat utilization with other renewable energy sources, such as solar panels or wind turbines, could be a key focus of future research to create more efficient and sustainable energy systems.

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