Analysis of Bio Phase Change Material (PCM) Utilisation in Air Conditioning System on Energy Consumption

Luh Putu Ike Midiani[1], I Wayan Adi Subagia[2], I Gede Artha Negara[3],
I Nengah Ardita[4], I Wayan Suirya[5],
and I Gusti Agung Made Adhyatmika Wijaya[6]

[1,2,3,4,5,6] Mechanical Engineering Department, Politeknik Negeri Bali, Bali, Indonesia
putuikemidiani@pnb.ac.id

Abstract. Cooling systems such as split AC are currently one of the devices widely used in commercial and residential buildings. However, high energy consumption, especially during peak loads, is a major problem that has a direct impact on energy efficiency and operational costs. Therefore, innovation is needed to improve AC work efficiency, one of which is through the use of thermal energy storage technology using Phase Change Material (PCM). This study aims to determine the influence of PCM on the efficiency of the air conditioning system, especially in reducing energy consumption. Subsequently, the control conditions were tested by operating the AC system under conditions without bio PCMs at no load and at the specified load. Testing with bio PCM is done by operating the AC system while adding bio PCM at the same load. Each test scenario (with and without bio PCM) will be repeated several times for 8 hours to ensure data reliability and minimise random variations. The results showed that the COP of AC without bio PCM, without bio PCM with load, with bio PCM, and with bio PCM and load are respectively 4.68, 4.65, 4.61, and 4.63. The energy consumption is, respectively, 0.06528 kWh, 0.06663 kWh, 0.0673 kWh, and 0.0665 kWh. It can be said that bio PCM resists an increase in the cooling load, thereby resisting an increase in energy consumption, increasing the COP of the air conditioning system.

Keywords: Air Conditioning, Bio PCM, Energy Consumption

1 Introduction

Today, the global landscape is faced with two fundamental challenges that are intertwined: the exponential growth of the human population and the alarming acceleration of climate change. Both are putting significant pressure on various sectors of human activity, including the need for thermal comfort in the built environment. Along with increased urbanisation and social mobility, the demand for air conditioning (AC) systems has dramatically surged to unprecedented levels. In developing countries, improved living standards are directly correlated with the widespread adoption of air conditioning. In contrast, in developed countries, air conditioning has become an essential component in households and offices. As a concrete example, reports from the

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International Energy Agency (IEA) consistently highlight that the building sector is one of the largest energy consumers globally. Conventional air conditioning is a significant contributor to energy consumption, accounting for more than 15% of total global electricity consumption, with a projected increase in the future (IEA, 2021).

The significance of air conditioning in maintaining comfort and productivity is undeniable. Conventional air-conditioning systems, which generally operate based on the vapour-compression cycle, are known to be passive yet huge consumers of energy. The thermodynamic efficiency of this cycle, despite significant improvements due to technological advancements, still has inherent limitations. These limitations, coupled with the constant operational demands of drastically lowering the room temperature, result in a substantial carbon footprint through greenhouse gas emissions, both from the electricity consumption itself (especially if the energy source comes from fossil fuels) and from the potential leakage of refrigerants that often have a very high global warming potential (GWP) (Zhu et al., 2022). These dual impacts—the high running costs that burden households and industry, as well as the contribution to environmental degradation through increased greenhouse gas emissions and ozone layer depletion—have fueled an urgent search for smarter, efficient, and environmentally friendly refrigeration solutions (Saidur et al., 2009).

The need for more efficient and sustainable cooling solutions has become a necessity. Various strategies have been proposed and developed, ranging from improved compressor efficiency to the use of more environmentally friendly refrigerants and the integration of renewable energy sources. However, one of the most promising approaches that has received extensive scientific attention in recent decades is the utilisation of Phase Change Materials (PCMs) in air conditioning systems and other thermal applications.

Fundamentally, PCMs are substances that can absorb and release significant amounts of heat energy at relatively constant temperatures during their physical change processes, such as from solid to liquid or from liquid to solid (Pudjiastuti, 2015; Sharma et al., 2009). This phenomenon is known as latent energy storage. Unlike conventional materials that store heat energy through an increase in temperature (sensible heat storage), PCMs can absorb heat without experiencing an increase in temperature during their transition phase. This allows PCMs to act as an effective ‘heat sink’ at a certain operational temperature, and then release the stored heat when temperature conditions change. This capability presents an opportunity to integrate them with air conditioning systems to enhance their efficiency and performance.

The basic concept of PCM utilisation in an air conditioning system can be described as an air conditioning unit equipped with PCM that melts at 24°C. When the room temperature rises above 24°C, the PCMs will begin to absorb heat from the room environment and undergo the melting process. During this melting process, the PCM will absorb a large amount of latent heat energy, effectively delaying or reducing the need for the AC compressor to work hard to cool the room. When the room temperature drops again, the melted PCMs will begin to refreeze, releasing the stored latent heat to the environment. In this way, the PCMs can function as a thermal buffer, stabilising the room temperature and reducing the temperature fluctuations that often trigger repeated AC activations. Ariwibowo et al. (2022) in their research demonstrated that integrating

PCMs into air conditioning systems can lead to significant reductions in energy consumption, reaching over 20 percent under certain operational conditions, while also contributing to improved thermal comfort for occupants.

The integration of PCMs into building elements, such as walls, ceilings, or floors, also offers substantial benefits. In this scenario, PCMs embedded in building materials can absorb excess heat from sunlight during the day and release it back at night, when air temperatures are lower. This passive cooling approach can significantly reduce the cooling load on conventional air conditioning systems, especially in areas with large diurnal temperature variations (Cabeza et al., 2015). For example, the use of paraffin-based PCMs that fuse at around 25-26°C integrated into building walls can absorb solar heat that penetrates through windows, thus keeping interior temperatures comfortable without the need for intensive air conditioning activation until late afternoon or evening.

The selection of the right type of PCM is a crucial aspect that largely depends on the specific application and operational conditions. PCMs can be categorised into three main groups based on their chemical composition: Organic PCMs (e.g., paraffins, fatty acids, fatty alcohols), inorganic PCMs (e.g., salt hydrates), and eutectic PCMs (mixtures of two or more components that fuse at temperatures lower than the melting point of each component). Each category has its own advantages and disadvantages regarding latent energy storage capacity, phase change temperature range, thermal conductivity, cyclical stability, toxicity, and cost (Zalewski et al., 2018). Paraffins, for example, offer high latent energy capacity and good chemical stability, but have relatively low thermal conductivity and flammability. Salt hydrates, on the other hand, have better thermal conductivity and a wide range of melting points, but are prone to supercooling and phase segregation issues during repeated phase change cycles (Kenisarin & Mahkamov, 2013).

The combination of PCMs with materials having high thermal conductivity, such as graphite or carbon fibre, through encapsulation techniques, is often an effective solution (Sari et al., 2010). Encapsulation, either micro-encapsulation or macro-encapsulation, is an important method to overcome some of the inherent disadvantages of PCMs, such as leakage during the liquid phase, volume stability, and low thermal conductivity, while enabling the integration of PCMs into various media (e.g., sprayed into insulation foam or blended into composite materials) (Aragones et al., 2011; Farid et al., 2000).

The heat transfer mechanisms between PCMs and the room environment, as well as between PCMs and conventional cooling systems, must be carefully designed to ensure that thermal energy can be absorbed and released efficiently. Poor system design can lead to suboptimal utilisation of latent energy storage capacity, thus reducing the expected energy-saving benefits. Discussions on PCM thermal management, including optimisation of PCM storage unit geometry, cooling fluid flow rate, and operational control, are crucial research areas to maximise system performance (El-Sayed et al., 2019; Ling et al., 2017).

Among various PCM materials, virgin coconut oil (VCO) stands out due to its favourable thermal properties, such as robust thermal stability and significant melting heat capacity (Kahwaji & White, 2019; Saleel, 2022). The potential applications of VCO as a PCM, including for interior temperature regulation, have been the focus of intensive research (Wonorahardjo et al., 2019). Virgin coconut oil (VCO) is an oil derived from coconut essence, processed hygienically without direct contact with fire and chemical additives, so that the essential content in the oil can still be maintained. The main components of VCO, around 92% are saturated fatty acids, including lauric acid (48.74%), myristic acid (16.31%), caprylic acid (10.91%), capric acid (8.10%), and caproic acid (1.25%) (Suryani et al., 2020).

This research specifically investigates further the feasibility and effectiveness of VCO as a PCM solution for energy consumption, energy efficiency, and COP of air conditioning systems, by comprehensively reviewing its encapsulation method and integration strategy into air conditioning systems.

2 Methodology

This research employs a quantitative approach, utilizing experimental methods through direct testing. The objective is to compare the performance of an air conditioning (AC) system equipped with bio PCM with a conventional AC system that does not use PCM, under light operational load conditions.

Samples and equipment used for research include a standard room air conditioner unit to be used as a test subject, PCM selected based on its operational temperature suitability and storage capacity, a controlled test room to ensure consistency of environmental parameters, temperature sensors (e.g., thermocouples or digital sensors) strategically placed in the room and on the air conditioner components to accurately record temperature data, and an energy consumption meter (e.g., power meter or watt meter) to measure the electrical power consumption of the air conditioner unit.

According to existing literature, PCMs are generally placed near the evaporator coil of air conditioners or distributed indoors to maximise thermal contact and heat absorption efficiency (Sharma et al., 2011; Ling et al., 2016). The test procedure starts from the preparation of the AC system installed in the test room, and the bio PCM is placed in a predetermined location. Subsequently, the control conditions were tested by operating the AC system under conditions without bio PCMs at no load and at the specified load. Room temperature and energy consumption data were recorded periodically during the predetermined test period. Testing with bio PCM is done by operating the AC system while adding bio PCM at the same load. Temperature and energy consumption data were recorded periodically. Each test scenario (with and without bio PCM) will be repeated several times for 8 hours to ensure data reliability and minimise random variations. The placement of measurement instruments, including temperature sensors and energy meters, is illustrated in Figure 1.

The collection of temperature data is done with the following codes: refrigerant temperature when entering the compressor (T1), refrigerant temperature when exiting the compressor (T2), refrigerant temperature when entering the expansion device (T3), electrical voltage (V), electric current strength (I), and refrigerant temperature when entering the evaporator (T4), room temperature (T5), air temperature (T6).

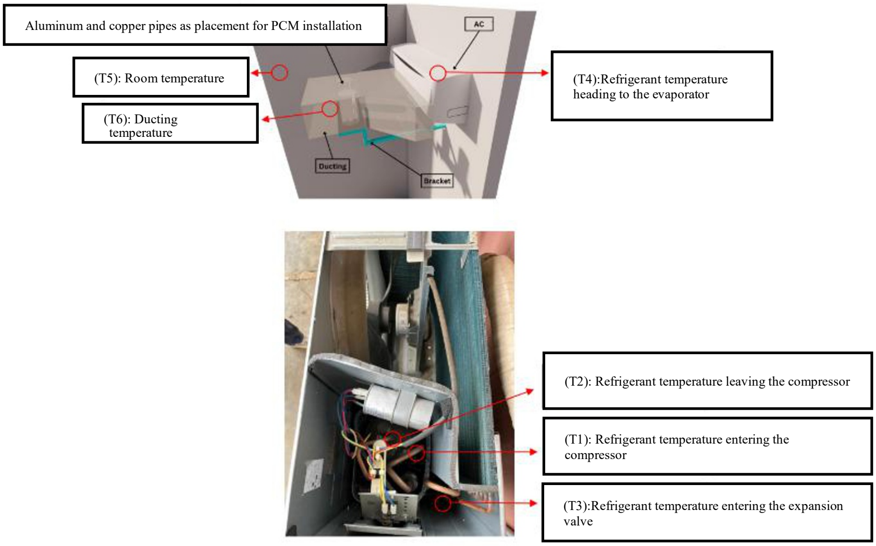

Figure 1. Instrument Placement

The performance of an air conditioning system is usually described by a coefficient of performance (COP), defined as the benefit of the cycle (amount of heat removed) divided by the required energy input to operate the cycle. The COP formula is as follows. (ASHRAE, 2009):

$$COP = \frac{ER}{W_{net}} \tag{1}$$

where :

ER = refrigeration effect (kJ/kg)
W_{net} = compression work (kJ/kg)

The energy consumption of the system indicates the energy used over time, calculated based on the following equation (Simbolon et al., 2022) :

$$P = V \times I \times \cos\varphi \tag{2}$$

$$E = P \times t \tag{3}$$

where :

P = power (Watt)
V = voltage (Volts)
I = electric current (Amperes)
$Cos\ \varphi$ = power factor
E = energy consumption (kWh)
t = time (hour)

3 Result and Discussion

The tests conducted were divided into four categories: AC testing without bio PCM, AC testing without PCM with load, AC testing with bio-PCM, and AC testing with bio PCM and load. The test results obtained included the air temperature and refrigerant temperature of split air conditioners, as shown in four test criteria in Figure 2.

Figure 2. The Test Results

Figure 2 states that without the application of PCM, the lowest room temperature that can be achieved is 12.6°C, and when a load is applied, the lowest room temperature achieved is 14 °C. Air conditioners with the application of PCM, the lowest room temperature that can be achieved is 15.9 ºC, and when given a load, the lowest room temperature is 14.1 ºC.

In the four types of AC testing, namely without the application of bio PCM, without bio PCM with load, with bio PCM, and with bio PCM and load with the highest room temperature achieved in total around 21 ºC. Furthermore, to achieve the lowest room temperature from testing without bio-PCM, with bio-PCM without load, and with bio-PCM given a load takes 10-15 minutes. Meanwhile, the type of test with bio PCM without load to achieve the lowest room temperature takes about 20-25 minutes. From these explanations, it can be stated that the bio PCM applied still acts as a cooling load for the air conditioning system. However, when applying bio PCM with a load, the ability to achieve the lowest temperature and the time required have the same capabilities. Therefore, it can be stated that the application of bio PCM when there is a load can maintain the stability of the room temperature.

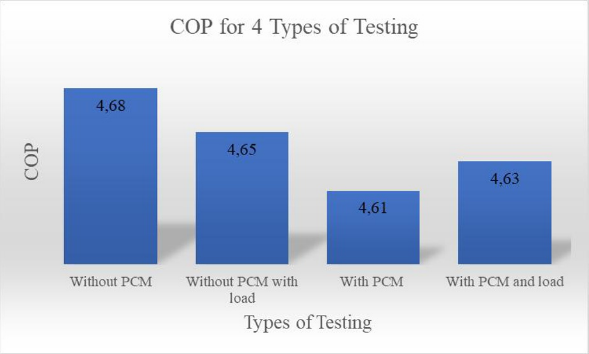

Figure 3. COP Systems

Figure 3 shows the COP for the four types of testing. The COP of AC without bio PCM and without load is used as the COP benchmark, which is 4.68. The COP of AC decreases with the addition of cooling loads. In air conditioners with the addition of bio-PCM, the COP system decreases again. This is because bio PCM becomes an additional cooling load. However, when the air conditioning system utilizes bio PCM and applies cooling loads, the COP system increases again. It can be said that bio PCM plays a role in resisting the increase in cooling loads, thereby increasing the COP of the air conditioning system.

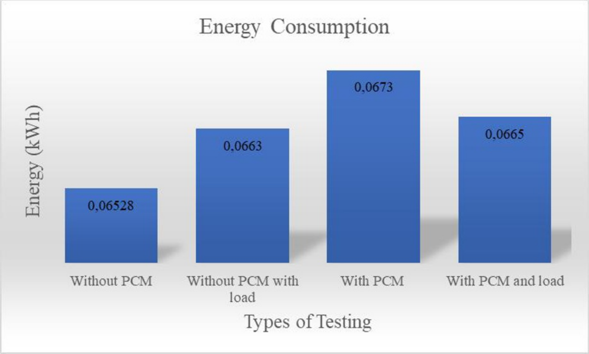

Figure 4. Energy Consumption

Energy consumption for the four types of tests is shown in Figure 4. A high COP value will be achieved if the cooling energy produced exceeds the energy required for cooling. This is illustrated in the energy consumption graph. Since the addition of bio-PCM is considered a load, energy consumption will increase to overcome the resulting cooling load. However, when PCM is applied to an air conditioner that also has an added load, the COP value is almost comparable to the COP of an air conditioner without PCM with a load. It can be said that PCM resists an increase in the cooling load, thereby resisting an increase in energy consumption.

4 Conclusion

The tests conducted based on four types of testing yielded the following conclusions. Bio PCM, applied, still acts as a cooling load for the air conditioning system. However, when applying bio PCM with a load, the ability to achieve the lowest temperature and the time required have the same capabilities. Therefore, it can be stated that the application of bio PCM when there is a load enables the room temperature to maintain stability. The COP of AC without bio PCM, without bio PCM with load, with bio PCM, and with bio PCM and load are respectively 4.68, 4.65, 4.61, and 4.63. It can be said that bio PCM plays a role in resisting the increase in cooling loads, thereby increasing the COP of the air conditioning system. The energy consumption of AC without bio PCM with load, with bio PCM, and with bio PCM and load is respectively 0.06528 kWh, 0.06663 kWh, 0.0673 kWh, and 0.0665 kWh. The addition of bio PCM is considered a load, as energy consumption will increase to overcome the cooling load. However, when PCM is applied to air conditioners that also have additional loads, the COP value is almost comparable to the COP value of air conditioners without PCM that have loads. It can be said that PCM resists an increase in the cooling load, thereby resisting an increase in energy consumption. For bio PCM improvement, additional substances are recommended to improve the performance of bio PCM.

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