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Energy Efficiency with Internet of Things Based Fuzzy Inference System for Room Temperature and Humidity Regulation

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ABSTRACT

Energy consumption is a crucial aspect in the effort to optimize the utilization of resources and reduce energy wastage. Focusing on energy efficiency can result in operational cost savings, a reduction in greenhouse gas emissions, and support for environmental sustainability for future generations. Therefore, it is important to consider energy efficiency in daily life, especially in the use of electricity for electronic devices. This research aims to compare the energy efficiency of two different approaches to Air Conditioner (AC) usage: the manual method and the fuzzy logic method. The manual method involves eight tests with direct power measurements over a 30-minute period at various AC temperature settings, namely 18°C, 20°C, 23°C, 24°C, 25°C, 26°C, 27°C, and 30°C. On the other hand, the fuzzy logic method involves six tests allowing for dynamic temperature adjustments based on room conditions. The research findings indicate that the fuzzy logic method achieves lower average power consumption, except at 30°C, where the manual method is slightly more efficient (a difference of 140,745 watts). This difference is primarily attributed to the "cooling and fan" mode used at lower temperatures in the manual method, resulting in higher power consumption. Furthermore, this research reveals the potential of the fuzzy logic in optimizing AC power usage based on real-time conditions, achieving approximately a 41.96% energy savings. The primary contribution of this study is to provide practical insights into how the fuzzy logic method can significantly reduce AC energy consumption, support energy efficiency efforts, and contribute to environmental sustainability.

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1. INTRODUCTION

The Internet of Things (IoT) has become one of the most prominent technologies in the evolving digital era (1-5). IoT has transformed the way humans interact with devices and systems in their surroundings, ranging from smart homes to autonomous vehicles (6-8). IoT is often integrated with artificial intelligence (AI) (9). One area where IoT has made a significant contribution is in enhancing comfort and energy efficiency in the environment, especially in regulating room temperature and humidity (10-12). The regulation of room temperature and humidity is a crucial aspect of creating a comfortable and productive environment. Excessive heat or cold, as well as inappropriate humidity levels, can disrupt the comfort and health of room occupants. Moreover, inefficient regulation of temperature and humidity can lead to energy wastage, negatively impacting the environment, both directly and indirectly.

Currently, tools widely available in the market tend to favor manual settings, such as the implementation of the ON/OFF system. This manual method is inefficient in energy usage because it is unresponsive to minor temperature fluctuations, does not consider humidity, and results in significant energy wastage. The consequences include increased energy costs, excessive utilization of natural resources, inconvenience to room occupants, and an overall decrease in energy efficiency.

In an effort to effectively enhance the regulation of room temperature and humidity, Fuzzy Inference Systems (FIS) have emerged as efficient solutions (13-15). FIS is a regulatory method rooted in fuzzy logic, enabling machines to make decisions based on multiple influencing variables (16). In the context of regulating

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room temperature and humidity, FIS empowers IoT devices to intelligently manage indoor temperature and humidity based on specified parameters. Therefore, in this study, researchers will investigate energy consumption when employing FIS and IoT to control room temperature and humidity using AC. Energy consumption plays a pivotal role in achieving resource efficiency (17-19).

This research aims to reduce unnecessary energy consumption, safeguard the environment, promote sustainability, enhance productivity, foster technological innovation, and improve quality of life. By developing more efficient solutions, this research yields benefits in the form of energy conservation, reduction in greenhouse gas emissions, enhanced operational efficiency, adoption of intelligent technologies, and the creation of a more comfortable and healthier environment. This objective directs the transition towards wiser, more sustainable, and more impactful energy utilization for individuals. This research represents a continuation of prior studies on temperature and humidity control systems utilizing FIS and IoT-based AC (20). However, this study specifically concentrates on devising an effective and efficient AC control system for regulating room temperature and humidity using Tsukamoto's FIS and IoT methods, without evaluating the efficiency of energy consumption, both in the short-term and long-term usage (20). Particularly, it addresses the utilization of long-term AC systems, which are categorized as inefficient (21-23).

Previously, Orhan Ekren and Serhan Küçüka had conducted research on fuzzy logic-based control algorithms for regulating compressor speed and Electronic Expansion Valve (EEV) opening percentages in chiller systems. This research aimed to enhance the efficiency of the chiller system by utilizing a Variable Speed Scroll Compressor (VSSC) and EEV. Fuzzy logic algorithms were employed to govern the compressor speed based on the chiller water output temperature, while the opening percentage of the EEV was controlled based on the refrigerant superheat value at the evaporator outlet. The study's findings revealed a performance improvement of 17% when compared to thermostatically controlled fixed-speed chiller systems, as well as superior control over water temperature achieved through the use of fuzzy-controlled VSSC (24).

Ahmed et al. (25) proposed a scheme utilizing fuzzy logic to control central air conditioning and maintain room temperature and humidity close to predefined targets. This aims to reduce electrical energy consumption and create comfort in various rooms of different sizes and conditions. The result is comfortable rooms with higher energy efficiency. Subsequently, Riyadh Waheed et al. (26) highlighted the role of fuzzy logic-based controllers in enhancing the efficiency of air conditioning, especially in classrooms. The research findings indicated that fuzzy logic-based controllers are superior in regulating room temperature and humidity compared to traditional controllers.

By the use of fuzzy logic controllers in air conditioning systems Francis et al. (27) have successfully reduced electricity consumption by adjusting the compressor speed and operating mode according to environmental conditions and user needs. This demonstrates significant potential for energy savings in air conditioning systems, particularly in urban areas, while considering various input parameters such as temperature, occupancy, time, and weather conditions. A review by Belman-Flores et al. (28) stated that the use of fuzzy logic controllers in refrigeration and air conditioning systems (RACs) has proven their ability to improve thermal efficiency compared to classical controllers like ON/OFF and PID. Computer simulations and experimental tests also showed that the use of fuzzy controllers can reduce energy consumption.

In another study, Nasution (29) evaluated vehicle AC systems using Fuzzy Logic Control (FLC) algorithms to continuously regulate compressor speed. Experiments were conducted with variations in set point temperature, internal heat load, and compressor speed. The results demonstrated that the utilization of FLC led to significant energy savings and improved indoor comfort when compared to conventional ON/OFF controls. This technique holds the potential to enhance the efficiency and overall performance of passenger vehicle AC systems. Furthermore, this research is corroborated by a study conducted by Khayyam et al. (30) who also discussed the development of intelligent energy management systems for optimizing the utilization of AC systems in vehicles. The system incorporates data from various information systems to make intelligent decisions, including predicting road power demand and employing intelligent control strategies. Simulations indicate that this system can achieve energy savings of up to 12% when compared to conventional systems and other energy management systems.

Additionally, the efficacy of Fuzzy logic in attaining energy efficiency is further supported by other studies, such as those conducted by Chu et al. (31). This study proposed the use of the Least Enthalpy Estimator (LEE) in the Fan Coil Unit (FCU) controller in Heating, Ventilating, and Air Conditioning (HVAC) systems to conserve energy and maintain thermal comfort levels. The LEE-based fuzzy FCU controller demonstrates the ability to accurately predict loads and adjust the FCU system's output based on temperature and relative humidity. Through experimentation, this controller successfully achieved the thermal comfort, energy efficiency, and reliability necessary in FCU control systems.

Regarding the efficiency of fuzzy logic, Saini et al. (32) also provided statements in their research supporting the efficiency achieved by fuzzy logic. Their study utilized fuzzy logic to control loads in a Solar Home System with the aim of efficiently managing energy usage. Test results indicated that the use of fuzzy logic could reduce power consumption for lighting and fans compared to control without fuzzy logic.

While previous research has attempted to apply FIS and IoT in various contexts, such as solar home systems, chiller systems, or vehicle air conditioning, there is still a gap in research that focuses on room temperature and humidity regulation using AC with a comprehensive assessment of energy consumption. Previous studies often did not compare energy consumption between manual systems and fuzzy-based systems to understand the potential energy savings that can be achieved.

Therefore, in this study, we specifically examine room temperature and humidity regulation using AC while evaluating energy consumption. This research makes a stronger contribution to developing more efficient solutions for sustainable environmental control through AC usage by attempting to compare energy consumption between manual and fuzzy-based systems to determine potential energy savings.

2. METHOD

The subsections outlined in this method section encompass three main aspects: the research stages, the application of fuzzy Tsukamoto, the specifications of the AC system used, and the methods employed for energy consumption analysis.

2. 1. Research Stages

This research builds upon prior studies that primarily focused on assessing the environmental impact of AC systems following the implementation of fuzzy logic. The research process encompassed several stages, including requirements analysis, tool and application design, tool and application development, fuzzy logic integration into the tools, and testing the tools' impact on room conditions. These stages were systematically evaluated to attain the research objectives.

The developed tools and applications were then utilized to collect energy consumption data within AC systems. Subsequently, this data underwent analysis to gain insights into the influence of fuzzy logic on energy efficiency and the potential savings it can offer. As a result, this study aims to provide comprehensive and detailed insights into the impact of fuzzy logic on energy efficiency within AC systems. An overview of the research stages is illustrated in Figure 1.

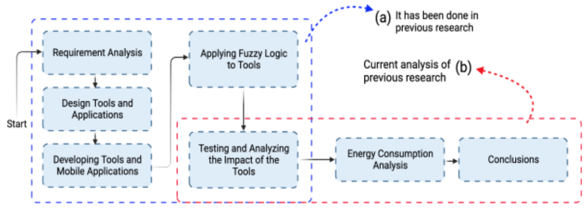


Figure 1. The research comprises two sets of stages: (a) stages that were previously conducted [20], and (b) the more advanced stages implemented in this study

2. 2. Fuzzy Tsukamoto

The Fuzzy Tsukamoto model is a fuzzy logic-based control approach developed in past decades (33, 34). This approach combines the principles of fuzzy logic with intuitively defined linguistic rules to control complex and ambiguous systems. Fuzzy Tsukamoto utilizes the concept of fuzzy membership to depict uncertainty in system inputs and outputs. This concept allows system variables to exhibit varying levels of membership in different categories. For instance, in room temperature control, variables like "*cold*" and "*hot*" can have membership levels or fuzzy sets such as "*slightly cold*", "*medium cold*", "*slightly hot*", and "*medium hot*" (35). These membership levels describe the degree to which an input or output value belongs to a particular category. Linguistic rules are employed in the Fuzzy Tsukamoto model to establish connections between system inputs and outputs. These rules comprise conditional statements that link input conditions with output actions. For instance, "*IF the room temperature is low, THEN the heating rate is increased*". These rules are formulated based on expert knowledge in the relevant domain and are represented in the form of fuzzy sets.

Essentially, Fuzzy Tsukamoto is one of three models within FIS. The other two models are Mamdani and Sugeno reported in literature (36-38). FIS serves as a mathematical framework or model employed for implementing fuzzy logic in decision-making or system control (39, 40). FIS encompasses several key components that collaborate to generate outputs based on fuzzy inputs. FIS can find applications in various domains involving decision-making, system control, and the processing of uncertain or ambiguous data. Within FIS, existing human knowledge or expertise is represented in the form of fuzzy rules and applied to generate outputs based on given input conditions. FIS enables systems to process fuzzy data by amalgamating human knowledge with mathematical techniques, leading to more adaptable and flexible decision-making.

The control process utilizing Fuzzy Tsukamoto comprises several stages. Initially, the system input is transformed into fuzzy sets using membership functions. This initial stage is referred to as the fuzzification stage (41-43). Subsequently, linguistic rules are employed to establish connections between the fuzzy sets of inputs and the desired output. The subsequent stage involves the inference process, during which linguistic rules are assessed to generate the appropriate level of output membership. Lastly, the results of the inference are converted into crisp values through defuzzification, thereby producing numerical output that can be utilized for system control.

2. 2. 1. Fuzzification Fuzzification is the process of converting crisp (non-fuzzy) variables into fuzzy variables by using membership functions (20, 44, 45). Fuzzification allows mathematical representation of uncertainties in the system using fuzzy sets (44-48). The crisp variables that will be used as system inputs are converted into fuzzy sets using the membership function. The membership function associates the crisp value with the membership level in the fuzzy set. Each fuzzy set consists of a set of possible values for the relevant crisp variable. The membership function in fuzzification describes the extent to which a crisp value belongs to a fuzzy set. Membership functions are usually represented in the form of curves, such as triangular curves (49), trapezoidal curves, or other curves corresponding to the characteristics of variables and their domains. This curve shows the membership levels of variables in a fuzzy set at various points of their value.

Fuzzification is an important step in the fuzzy logic-based control process, as it converts crisp data into fuzzy representations that fuzzy systems can use to make decisions and produce appropriate outputs (50, 51). In combination with fuzzy inference and defuzzification, fuzzification assists fuzzy systems in modeling and controlling complex systems by taking into account the uncertainty and ambiguity inherent in system inputs. The fuzzification process is written in Equation 1.

$$x = fuzzifier(x_0) \quad (1)$$

where x_0 is a firm value vector of an input variable, x is a fuzzy set vector defined as a variable, and fuzzifier is a fuzzification operator that converts a firm value to a fuzzy set (52).

2. 2. 2. Machine Inference At the inference system stage, fuzzy rules are used to draw conclusions based on fuzzy set theory and fuzzy rules in the form of IF-THEN statements (53). This IF-THEN statement can usually also consist of one or more antecedents (also called premises) located within the IF section with one or more consequent (also called conclusions) located within the THEN section. In general, a rule can have multiple premises associated with an AND statement (conjunction), an OR statement (disjunction), or a combination of the two. In this case, Zadeh identified three basic operators used in fuzzy rules, namely the AND, OR, and NOT operators (54, 55). The AND operator is used to retrieve the minimum element between the two fuzzy sets involved (56). In this context, the AND operator results in the lowest membership level of the corresponding fuzzy set (Equation 2). The OR operator, on the other hand, is used to find the maximum element between two fuzzy sets. Using the OR operator, the highest membership level of the associated fuzzy set is taken (Equation 3). The NOT operator is used to subtract the value of 1 with a negated fuzzy element. In other words, if a fuzzy set has a membership level of α, then using the NOT operator, the membership level becomes 1 – α (Equation 4) (57). In the context of this study, the AND operator is applied to each formed fuzzy rule. The use of this AND operator results in the lowest membership value of the fuzzy set involved in each of those rules. Mathematically, the AND operator can be described using Equation 2.

$$\mu K \cap L = \min(\mu K[x], \mu L[x]) \quad (2)$$

$$\mu K U L = \max(\mu K[x], \mu L[x]) \quad (3)$$

$$\mu K' = 1 - \mu K(x) \quad (4)$$

2. 2. 3. Defuzzification Defuzzification is a transformation that restates the output from a fuzzy domain into a crisp domain. Fuzzy output is obtained through the execution of some fuzzy membership functions. There are several methods that can be used in the defuzzification process, namely **(1)** *Weighted Average Method* (58-60), a method that calculates the average value by assigning a certain weight or weight to each element in the data set aimed at reflecting the relative importance or contribution of each element to the final result, **(2)** *Mean-Max Membership* (61-63), a method that combines several overlapping membership rules by taking the maximum value of each set membership at a point, then calculate the average of those maximum values, **(3)** *Centroid (Center of Gravity) Method* (64, 65), a method that calculates the center point (centroid) of a membership set using the weighted principle based on membership level. The membership value of each point on the set is multiplied by the position of that point, then added and divided by the total membership value, **(4)** *Height Method (Max-Membership Principle)* (66, 67), a method that takes the maximum value of the membership level in a membership set as a representation of the membership value of the entire set, **(5)** *Center of Sums* (68-70), a method that calculates the center of input values by adding input points and dividing them by the total number of inputs, **(6)** *First (or Last) of Maxima* (66, 71, 72), a method that selects the first (or last) point at which the membership level reaches the maximum value of a membership set as a representation of the overall membership value of that set, and **(7)** *Center of Largest Area* (73, 74), a method that calculates the center of the area of a membership set by taking the midpoint at the interval with the largest set area. The defuzzification method used in this study is the *Weighted Average* written in Equation 5.

$$x^* = \frac{\sum_{i=1}^{n} \mu c(\bar{x}_i).\bar{x}_i}{\sum_{i=1}^{n} \mu c(\bar{x}_i)} \quad (5)$$

where $\sum_{i=1}^{n}$ represents an algebraic sum with respect to the membership function of *n* fuzzy sets. This method has the limitation that it can only be used on fuzzy sets with symmetric membership functions (75).

2. 3. AC Specifications Used As explained in the introduction, this study focuses on the analysis of energy consumption on the use of AC as an air conditioner. AC performance will be analyzed and evaluated to understand the impact of its use on power consumption after fuzzy logic is enacted in regulating AC values. One important step in power consumption analysis is obtaining the associated AC specifications. To collect AC specifications, first of all, it is necessary to know the electrical power consumed by the air conditioner. This information can usually be found on the technical specifications of the AC or on the label attached to the AC unit itself. This electrical power is expressed in units of watt (W) and is an important indicator for understanding the extent to which AC consumes power while operating.

Another important specification to know is the AC efficiency factor (76-78). The efficiency factor describes the level of efficiency of an AC in producing cooling relative to the power consumed (76). The efficiency factor is usually expressed as a percentage and can affect power consumption significantly. Therefore, knowing the efficiency factor of AC allows for more accurate calculations in estimating AC power consumption at different temperatures.

Based on the Decree of the Minister of Defense of the Republic of Indonesia No. 782/VIII/2015, the power standard for AC is calculated based on Paarden Kracht (PK) where 1 PK is equivalent to 0.7355 kW (79). While the AC used is equivalent to ½ PK, so ½ PK x 0.7355 kW = 0.368 kW. Then, the magnitude of ½ PK is equal to ±5000 BTU/h (British Thermal Units per hour) (80, 81). In addition, based on the reference read (82), the calculation of energy consumption per year can be obtained by Equation 6.

$$\text{AE} = \frac{Q*t}{EER} \quad (6)$$

where *AE* stands for *"Annual Energy"* which refers to the total energy consumed or used by a system, device, or equipment in a one-year period. *Q* is the Capacity that represents the cooling capacity or cooling load of the air conditioner. This capacity is measured in units such as BTU/h, kilowatts (kW), or tons. Capacity describes the amount of heat that an AC can remove in a given period of time. While *t* (operating time) refers to the operating time of the air conditioner. This is the amount of time that AC is used or operating in units such as hours, minutes, or seconds. While Energy Efficiency Ratio (*EER*) is the ratio between the cooling capacity of AC and its input power. To calculate EER, you need to know the cooling capacity and AC input power in appropriate units, such as BTU/h and watts or kW. EER can be calculated using Equation 7 (83).

$$EER = \frac{\emptyset_{tci}}{P_t} \quad (7)$$

$$\emptyset_{tci} = \sum P_{ic} + (h_{w1} - h_{w2})W_r + \emptyset_{lp} + \emptyset_{li} \quad (8)$$

In Equation 7, $\emptyset_{tci}$ refers to the total cooling capacity required on the indoor side, while P_t describes the total power consumed by the equipment under test. While $\emptyset_{tci}$ obtained using Equation 8. The P_{ic} reflects the total power entering the indoor side test chamber, including lighting power, electrical power consumed by the equipment, and heat generated by compensation and humidification devices; h_{w1} is the specific enthalpy of water supplied to the indoor side test chamber, while h_{w2} describes the specific enthalpy of moisture condensed and exiting the chamber. P_{ic} is the condensation rate of water vapor in the room; $\emptyset_{lp}$ describes heat leakage that occurs through partitions that separate the inside of the room from the outside; $\emptyset_{li}$ described heat leaks occurring through the walls, floor, and ceiling of an indoor side test chamber (83).

By obtaining comprehensive AC specifications, including electrical power and efficiency factors, this study can continue a more detailed analysis of AC power consumption. The analysis will provide deeper insight into the extent to which the role of fuzzy logic in regulating AC values can affect the power consumption required to maintain room temperature at a certain level.

2. 4. Energy Consumption Analysis Method The test was carried out by turning on the AC for 30 minutes using the manual method and the fuzzy method. The calculation of electrical power is measured to obtain energy consumption. During the test, AC power was measured using a watt meter and recorded once every minute. One record per minute is assumed to represent the electrical power used in 1 minute, so to get the electrical power usage for 1 minute is calculated using Equation 9.

$$P_{minute} = P \ x \ 60s \quad (9)$$

In Equation 9, *P* is the electrical power used in 1 second. While P_{minute} is electrical power used in 1 minute. After getting the electrical power consumption per minute, the next calculated electrical power consumption during the test, which is ½ hour or 30 minutes. So, to obtain the total use of electrical power within 30 minutes obtained using Equation 10.

$$P_{\frac{1}{2}hour} = \frac{P_{minute} \ x \ 60 \ minutes}{2} \quad (10)$$

Or convert in 1 hour (60 minutes) using Equation 11.

$$P_{hour} = P_{minute}\ x\ 60\ minutes \quad (11)$$

If you want to convert it in kilowatt-hours (kWh), you can use Equation 12.

$$E_{(kWh)} = \frac{P_{hour}}{1600000} \quad (12)$$

Energy (E) in kWh is equal to power (P) in watts (W), multiplied by the time period t in hours, divided by 1000 as in Equation 13.

$$E_{(kWh)} = \frac{P_{(W)}\ x\ t_{hour}}{1000} \quad (13)$$

The watt meter used is as in Figure 2.

3. MAIN RESULTS

3. 1. Hypothesis The hypothesis of this study posits that the incorporation of fuzzy logic into room temperature and humidity regulation systems can lead to reduced resource consumption through several means. Firstly, fuzzy logic enables intelligent and adaptive control of temperature and humidity. Utilizing sensors to measure the current temperature and humidity, fuzzy inference systems can make informed decisions regarding whether to activate or deactivate heating or air conditioning devices. This prevents unnecessary energy usage when the temperature or humidity already falls within the desired range. Secondly, by employing linguistic variables and well-defined rules, fuzzy inference systems can finely tune temperature and humidity settings. For instance, if the room temperature is only slightly above the desired threshold, a fuzzy inference system can generate adjustments that proportionally reduce heating or air conditioning power. This mitigates excessive energy consumption associated with traditional ON/OFF methods.

Furthermore, fuzzy logic can take into account other factors influencing the comfort of room occupants. For example, if the external temperature is low but the humidity level is high, a fuzzy inference system can generate settings that slightly raise the temperature and lower the humidity to maintain comfort. By considering humidity, fuzzy inference systems contribute to optimizing overall energy utilization. Additionally, fuzzy logic enables the scheduling of energy usage based on observed usage patterns. For instance, if room temperature tends to increase during daylight hours, a fuzzy inference system can pre-condition the room by activating the heater or AC beforehand. This approach enhances energy efficiency and prevents excessive energy usage once the desired temperature is reached.

Figure 2. Watt Meter AC Digital Volt

3. 2. Discussion In this experiment, the air conditioner (AC) was operated for a duration of 30 minutes to assess its power consumption. The testing was conducted using two distinct methodologies: the manual approach and the fuzzy logic approach. The manual approach involved direct measurement and calculation of AC power consumption over the 30-minute period. Data for this method were manually recorded from wattage meter readings at 1-minute intervals, which were then used to compute the total AC power consumption. On the other hand, the fuzzy logic approach also recorded electrical power consumption through manual readings from the watt meter, similar to the manual method. However, the fuzzy method utilized a real-time fuzzy logic algorithm to regulate the AC's temperature.

The objective of these tests was to compare the energy consumption of each approach. The test results will yield valuable insights into managing AC power consumption, which can be leveraged for energy conservation and reducing operational costs.

3. 2. 1. Testing with Manual Method The manual method was assessed by measuring electrical power consumption at various AC temperature setpoints. A total of 8 tests were conducted, with each test performed at a distinct temperature setting: 18°C, 20°C, 23°C, 24°C, 25°C, 26°C, 27°C, and 30°C. Each test spanned 30 minutes to guarantee precise and uniform data collection. The testing procedure is illustrated in Figure 3.

Figure 3 displays the test conducted at an AC temperature setpoint of 25°C. The utilized modes in each test are "*Cooling mode*" and "*Fan mode*" both operating concurrently. In each test, data is meticulously recorded at 1-minute intervals based on the watt meter readings to

Figure 3. Manual Measurement Process of Electric Power at AC Temperature = 25°C

ensure comprehensive data collection. Variations in AC power consumption at various temperatures can be observed and analyzed. The fluctuations in electrical energy consumption, examined in all manual method tests, are summarized in Figure 4.

Figure 4 displays the results of testing the use of AC within a period of 30 minutes with two different modes, namely *"Cooling and fan mode"* and *"Fan only mode"*. In this test, the difference in energy consumption in the two modes is very clear. In *"Cooling and fan mode"*, the AC works to reach a set temperature setpoint, while running the fan for air circulation. This mode requires high power because the AC must cool the room by lowering the temperature to the desired setpoint and also maintain air circulation with the help of fans. The test results showed that the highest electrical power per second occurred at an AC temperature setpoint of 20°C, where power consumption reached 447.3 watts. This indicates that the lower the temperature to be achieved, the greater the power required by the AC in this mode. Meanwhile, in *"Fan only mode"*, the AC only functions as a fan without cooling the room. This mode results in much lower electrical power consumption compared to the *"Cooling and fan mode"* mode. The lowest electrical power occurs at an AC temperature setpoint of 30°C, where the power consumption per second is only 16.6 watts. This is because AC only uses power to run the fan without doing the cooling process, so the power requirement is lower. This test provides conclusions about the impact of using both modes on AC electrical energy consumption. The *"Cooling and fan mode"* mode is more suitable for achieving lower temperatures, but requires more power. On the other hand, the *"Fan only mode"* mode is suitable for situations where cooling is not required, and this helps in saving energy.

3. 2. 1. Testing with Fuzzy Logic Method

Testing with the fuzzy logic method requires several main components: fuzzy variables, fuzzy membership functions, and fuzzy rules. These components are used in three stages in Fuzzy Tsukamoto. Fuzzy variables consist of input and output variables. Input variables are used as input in the form of crisp values and are converted to fuzzy values in the fuzzification stage, while output variables are used in the defuzzification stage as the output of the fuzzy logic in the form of crisp values. The input variables used are room temperature and humidity, while the output variable is the AC temperature.

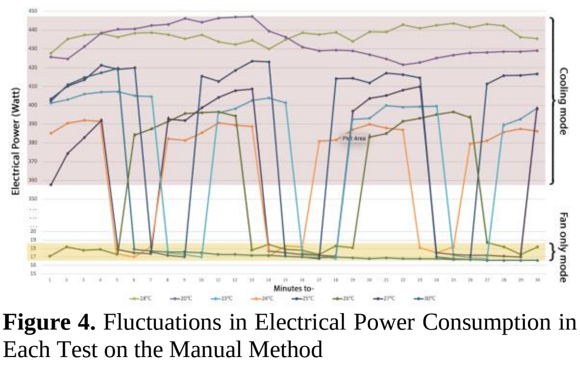


Figure 4. Fluctuations in Electrical Power Consumption in Each Test on the Manual Method

The selection of room temperature and humidity as input parameters in controlling AC temperature using fuzzy logic is based on physics and human comfort. Temperature affects human comfort and can impact AC efficiency, while humidity is also important because it can affect the feeling of warmth or cold. Proper control of both of these parameters can result in more efficient energy use and maintain indoor air quality.

To apply both of these parameters in fuzzy logic, they are divided into several fuzzy sets. The room temperature variable is divided into five fuzzy sets: Very Cold, Cold, Normal, Hot, and Very Hot. Meanwhile, the humidity variable is also divided into five fuzzy sets: Dry, Normal, Quite Wet, Wet, and Very Wet. On the output variable side, the AC temperature used has a range of 18-32°C, divided into three fuzzy sets: Cold, Normal, and Hot. The temperature curve is shown in Figure 5. The humidity curve is shown in Figure 6, and the AC temperature curve in Figure 7. As for the fuzzy rules with monotonic reasoning, there are a total of 25 rules corresponding to the two input variables, each having five fuzzy sets. The formed fuzzy rules are shown in Figure 8.

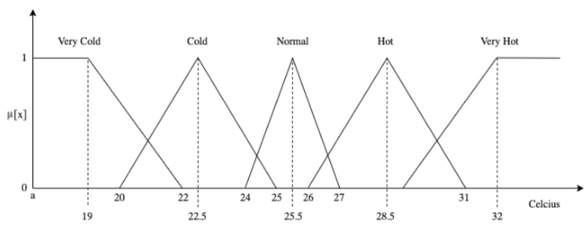


Figure 5. Room temperature membership function curve

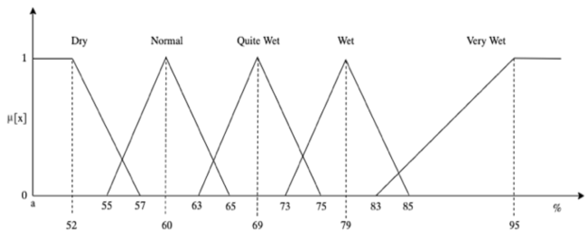


Figure 6. Room humidity membership function curve

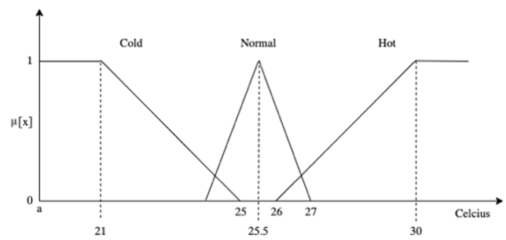


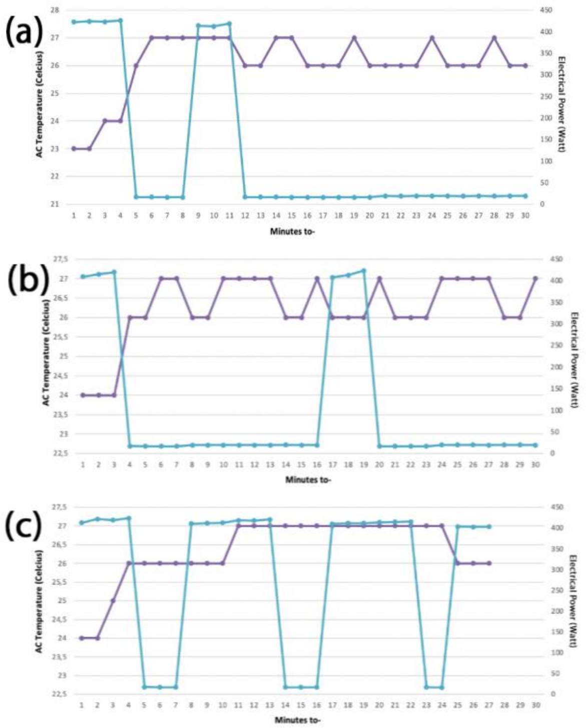
Figure 7. AC temperature membership function curve

AC Temp		Humidity				
		Dry	Normal	Quite Wet	Wet	Very Wet
Room Temp	Very Cold	Hot	Hot	Hot	Hot	Normal
	Cold	Hot	Hot	Hot	Normal	Normal
	Normal	Normal	Normal	Normal	Normal	Normal
	Hot	Normal	Normal	Cold	Cold	Cold
	Very Hot	Normal	Cold	Cold	Cold	Cold

Figure 8. Fuzzy rules

The membership function curves and fuzzy rules in Figures 5-8 are used to control room temperature, which will affect electrical power consumption. This fuzzy method was tested by measuring electrical power consumption on six tests. The temperature setpoint of the AC is not fixed and depends on the temperature and humidity conditions of the room during the test process. Similar to manual method testing, fuzzy method testing is also tested in a duration of 30 minutes in each test. This fuzzy method also presents 2 made air conditioners during the testing process, namely *"Cooling and fan mode"* and *"Fan only mode"*. The comparison of AC temperature setpoints to their electrical power consumption is listed in Figure 9.

Figure 9 shows the ratio of AC temperature setpoints to their electrical power consumption in all tests on fuzzy control methods. The value described by the graph of electrical power consumption is taken for 30 minutes at



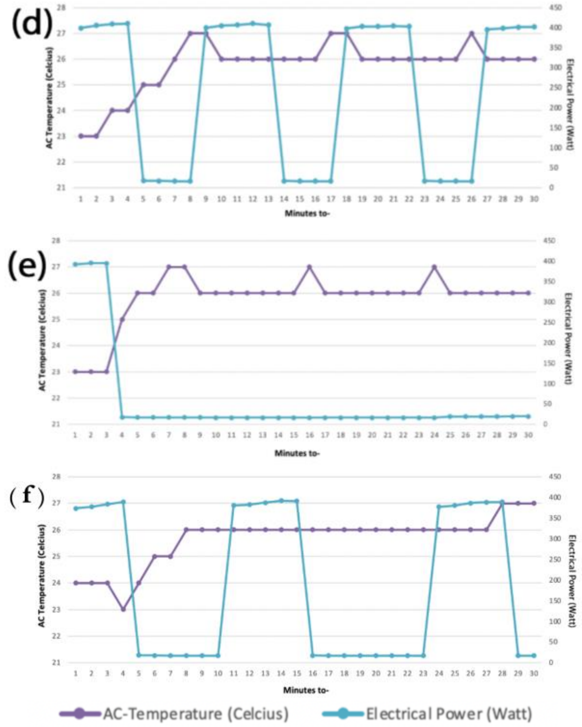


Figure 9. Comparison of AC Temperature Setpoint to Electric Power Consumption (Controlled Using Fuzzy Logic)

intervals of 1 minute. This means that the record is taken per minute for 30 minutes. During the testing process, the AC provided action in "cooling and fan" mode and "fan only" mode. A comparison of basic statistics in each mode can be seen in Figure 10.

In Figure 10, there are maximum power test results per second measured on six different tests. These results show that the highest value is reached at 425.6 watts, and this value is obtained when the AC operates in "cooling and fan" mode. The "cooling and fan" mode involves the AC in the process of cooling the room by running a fan for air circulation. Meanwhile, the lowest value in Figure 10 was recorded at 16.1 watts, and this value was obtained when the AC operated in "fan only" mode or only used a fan without cooling the process. In this mode, the AC does not require large power because its function is limited only to running the fan for air circulation without lowering the room temperature. To be able to evaluate each test, the total electrical power in each test using fuzzy control mode is shown in Figure 11.

The total electrical power consumption in Figure 11 is obtained by calculation using Equations 9 and 10. The highest electrical power consumption was obtained in the 3rd test with a consumption of 479347 watts or equivalent to 0.133 kWh (Equation 12). While the most efficient or lowest consumption was obtained in the 5th test with a total electrical power consumption of 98742

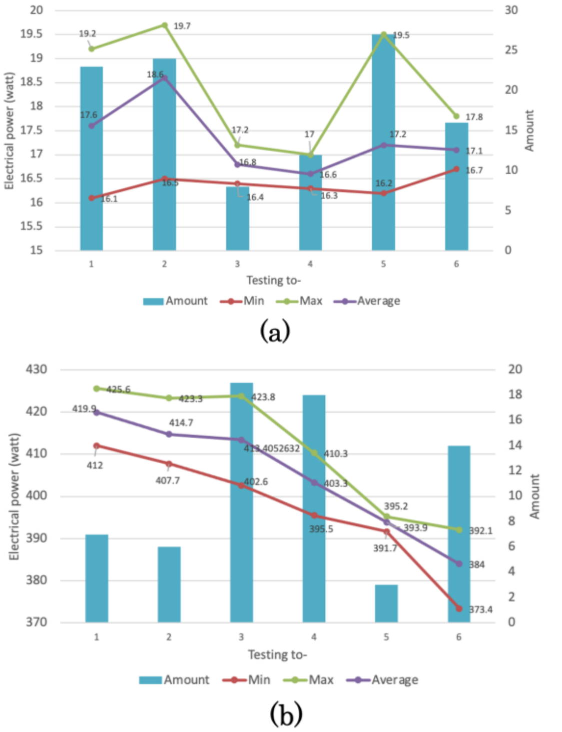


Figure 10. Comparison of maximum, average, and minimum electrical power in the test with fuzzy logic at (a). fan only mode; and (b). Cooling and fan mode"

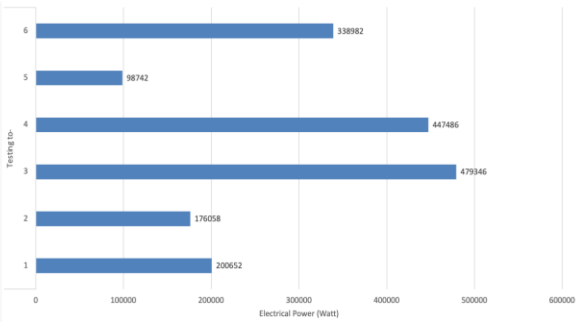


Figure 11. Total power consumption in each test with fuzzy logic control

watts or equivalent to 0.027 kWh. If averaged all electrical power consumption in all tests, then a value of 290211 watts or equivalent to 0.081 kWh is obtained. This value is categorized as more efficient when compared to manual methods that tend to consume a lot of electrical power. The results of the comparison between the total electric power consumption of the manual method with the average electric power consumption of the fuzzy method are listed in Figure 12.

Figure 12 shows that the average power consumption using the fuzzy method is lower than most tests on the manual method. Electric power consumption with the fuzzy method is only less efficient than using the

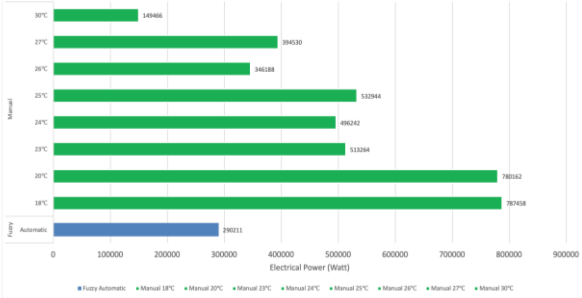


Figure 12. Comparison Between the Total Electric Power Consumption of the Manual Method with the Average Electric Power Consumption of the Fuzzy Method

manual method at the AC temperature setpoint = 30°C, which is with a difference of 140745 watts (0.039 kWh). While manual control at other AC temperature setpoints (18°C, 20°C, 23°C, 24°C, 25°C, 26°C, and 27°C) consumes much more electrical power when compared to the average power consumption in fuzzy control. The largest difference is in the manual control setpoint of 18°C and followed by the setpoint of 20°C. This is because at setpoints of 18°C and 20°C, the AC works in maximum conditions in *"Cooling and fan"* mode every second. This makes electrical power consumption also increase. Based on these results, it can also be concluded that electrical power consumption is also influenced by the amount of temperature that AC wants to produce. The smaller the desired temperature, the greater the power required by the AC, so this will make electrical energy consumption higher (84). To see the comparison of the difference in average electrical power consumption between these two methods (manual and fuzzy), it can be seen in Figure 13.

Figure 13 shows that the difference in average energy consumption is quite significant, reaching 209,820.75 watts (0.058 kWh). The average power consumption of the manual method is nearly twice that of the fuzzy method. Energy savings from the use of the fuzzy method amount to approximately 41.96%. A comparison with some previous studies is shown in Table 1.

Table 1 illustrates an interesting comparison across various studies regarding the use of fuzzy logic in controlling AC for energy savings. Different research outcomes show varying degrees of energy savings achievable through this approach. In 2018, a study by

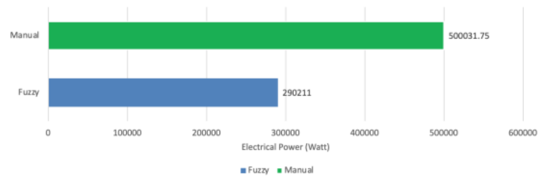


Figure 13. Comparison of the average total electrical power consumption of manual method and fuzzy method

TABLE 1. Comparison with some previous studies

Ref.	Method	Controlled device	Energy savings	Year
(85)	Fuzzy logic	Electronic devices, including the AC	40%	2018
(84)	Fuzzy logic	AC	33.55%	2019
(82)	Fuzzy logic	AC	25%	2020
(27)	Fuzzy logic	AC	62%	2022
(86)	Fuzzy logic	AC	16-25%	2023
This Research	Fuzzy logic	AC	41,96%	2023

Pratama and Sarno (85) on controlling electronic devices, including AC, with fuzzy logic successfully achieved 40% energy savings. Meanwhile, Berouine et al. (84) in 2019 and Shah et al. (82) in 2020 focused on AC control with fuzzy logic, achieving savings of approximately 33.55% and 25%, respectively. However, in 2022, a study by Francis et al. (27) achieved an impressive energy savings of 62% when controlling AC with fuzzy logic. Recent research in 2023 shows varying results, with energy savings ranging from 16% to 25% when controlling AC with fuzzy logic (86).

This study, conducted in 2023, achieved an energy savings of approximately 41.96% when controlling AC using fuzzy logic. A visual comparison of all the literature is shown in Figure 14.

When compared to several previous studies as outlined, this research demonstrates a commendable contribution, trailing behind only the study conducted by Francis et al. (27) with a difference of 20.04%. Nevertheless, these findings already indicate that the application of fuzzy logic in AC control can optimize electrical power usage intelligently by adapting operations to the actual needs of the room and environmental conditions. In the "cooling and fan" mode, the fuzzy method allows for the restriction of AC activity when the desired temperature has been achieved or considers room temperature fluctuations to reduce unnecessary power consumption. These results can also serve as a smart solution to reduce energy consumption across various contexts.

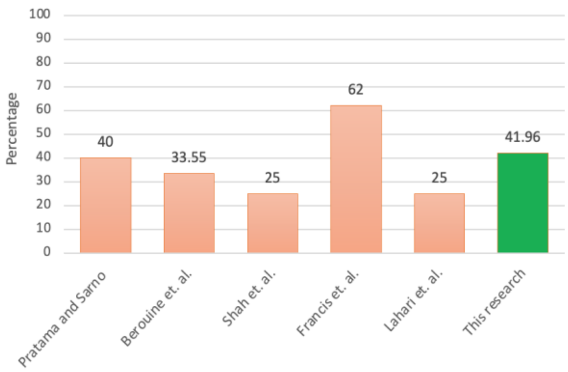


Figure 14. Comparison of Energy Savings with Previous Studies

4. CONCLUSIONS

The results of this study involved AC running for 30 minutes to observe power consumption by applying two different methods, namely the manual method and the fuzzy method. The manual method involves direct measurement and calculation of AC power used over a 30-minute period by manually recording data from watt meter readings at 1-minute intervals. Meanwhile, the fuzzy method also records electrical power consumption manually, but uses fuzzy logic algorithms to control the temperature of the AC in real-time. The test results show that the fuzzy method is more energy efficient than the manual method, except at a 30°C AC temperature setpoint. The difference is due to the *"Cooling and fan"* mode used at lower temperatures in the manual method, resulting in higher power consumption. Overall, the average test results of each method indicate that the fuzzy method has a lower average electrical power consumption compared to the manual method, with a significant difference. The use of the fuzzy method can achieve energy savings of approximately 41.96%. This demonstrates the potential of fuzzy methods in optimizing AC power usage in a smarter and adaptive manner based on room and environmental conditions.

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Persian Abstract

چکیده

مصرف انرژی یک جنبه حیاتی در تلاش برای استفاده بهینه از منابع و کاهش اتلاف انرژی است. تمرکز بر بهره وری انرژی می تواند منجر به صرفه جویی در هزینه های عملیاتی، کاهش انتشار گازهای گلخانه ای و حمایت از پایداری زیست محیطی برای نسل های آینده شود. بنابراین، توجه به بهره وری انرژی در زندگی روزمره، به ویژه در استفاده از برق برای وسایل الکترونیکی مهم است. هدف این تحقیق مقایسه کارایی انرژی دو رویکرد مختلف برای استفاده از تهویه مطبوع (AC) است: روش دستی و روش منطق فازی. روش دستی شامل هشت آزمایش با اندازه‌گیری مستقیم توان در یک دوره ۳۰ دقیقه‌ای در تنظیمات مختلف دمای AC، یعنی ۱۸ درجه سانتی‌گراد، ۲۰ درجه سانتی‌گراد، ۲۳ درجه سانتی‌گراد، ٢٤ درجه سانتی‌گراد، ۲۵ درجه سانتی‌گراد، ٢٦ درجه سانتی‌گراد، ۲۷ درجه سانتی‌گراد است. و ۳۰ درجه سانتی گراد از سوی دیگر، روش منطق فازی شامل شش آزمایش است که امکان تنظیم دمای دینامیکی بر اساس شرایط اتاق را فراهم می کند. یافته‌های تحقیق نشان می‌دهد که روش منطق فازی به جز در دمای ۳۰ درجه سانتی‌گراد که روش دستی کمی کارآمدتر است (تفاوت ١٤٠٧٤٥ وات) به میانگین توان مصرفی کمتری دست می‌یابد. این تفاوت در درجه اول مربوط به حالت "خنک کننده و فن" است که در دماهای پایین تر در روش دستی استفاده می شود و در نتیجه مصرف برق بیشتر می شود. علاوه بر این، این تحقیق پتانسیل منطق فازی را در بهینه‌سازی مصرف برق AC بر اساس شرایط بلادرنگ نشان می‌دهد و تقریباً ٤١.٩٦ درصد صرفه‌جویی در مصرف انرژی را به دست می‌آورد. سهم اصلی این مطالعه ارائه بینش های عملی در مورد اینکه چگونه روش منطق فازی می تواند به طور قابل توجهی مصرف انرژی AC را کاهش دهد، از تلاش های بهره وری انرژی حمایت کند و به پایداری محیطی کمک کند.