Implementation of Simple Artificial Intelligence in the Internet of Things for Energy Saving of Air Conditioner

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Abstract. In designing an AC control system, the designer usually faces two conflicting problems: convenient and saving problem. Sometimes the occupants of the room want to be cooler but it does not meet the standard of comfort. The consequence of setting a very low temperature will force the air conditioner to consume a significant amount of energy. This study proposes an efficient and comfortable AC control system in accordance with the comfort standards published by the American Society of Heating Refrigeration Air Conditioning Engineers (ASHRAE). To achieve savings, this system was developed using a hysteresis method guided by Fuzzy Logic to find the temperature and humidity points of the room that match the comfort standard IoT-based real-time. Finally, this system can save 30% AC energy consumption and achieve ASHRAE standard comfort.

Keywords: Air conditioner, Fuzzy Logic, Internet of Things.

1 Introduction

1.1 Background

The existing AC paradigm is optimizing the temperature even though the comfort of the room is not solely determined by temperature but a combination of temperature and humidity. The environmental thermal conditions for human dwelling refer to the American National Standards published by ASHRAE which define the range of indoor environmental conditions to achieve acceptable thermal comfort for building occupants. The standard was first published in 1966, and since 2004 it has been updated every three to six years. The latest version of the standard was published in 2017. The purpose of this standard is to determine the combination of indoor thermal environmental factors and personal factors that will result in a thermal environmental condition that is acceptable to most occupants of the space. Comfort in this study refers to the ASHRAE version of the comfort standard. The AC control paradigm in this study is to optimize AC energy consumption and add adaptive capabilities by conducting big data analysis to maintain the comfort specified by ASHRAE.

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This research will be described in 5 parts, i.e.: The Introduction explains the background of this research on how AC comfort and savings can be achieved. Meanwhile, the physical concept of comfort and savings is described in the materials and methods section. The research steps are outlined in the experimental design. The experimental results are described in detail in results and discussion and finally the conclusions and future research.

2 Materials and Methods

2.1 *ASHRAE* Standard Comfort

The ASHRAE standard curve shows the comfort temperature in each humidity is not at one point but it is in a certain temperature range, so temperature relaxation is the basis for optimizing AC energy which used in this study [1 - 3]. The temperature relaxation model (hysteresis) proposed in this study is a control that utilizes the thermal equilibrium properties of the room where energy consumption and room comfort are determined by the thermal load of the room and the performance of the air conditioner [4 - 7] The thermal equilibrium surface is defined as the initial state of indoor temperature when there is no disturbance [8]. When the compressor is turned on, the room temperature will decrease away from the thermal equilibrium surface. The effect of thermal stress begins to be felt which is indicated by the behavior of the indoor temperature which slopes before reaching the bottom point of thermal equilibrium. The indoor temperature becomes flat due to the cold air emitted by the air conditioner is proportional to the thermal pressure at the bottom point of the equilibrium. When the compressor is turned OFF, the rate of temperature rises up then it is damped slowly and increases slowly as it approaches the boundary of the thermal equilibrium surface. The nature of the equilibrium is all effects of thermal loads are aggregated in one coefficient symbolized by λ while the parameters related to the ability of AC to lift thermal loads are integrated in the coefficient μ. These two parameters were obtained by experimenting with the behavior of room temperature when the AC compressor was turned ON and OFF. In this study, room comfort and energy consumption in air conditioners is done by controlling the compressor because the compressor is the largest component in consuming energy. Compressor control is carried out using temperature relaxation. Its ON/OFF duty cycle is guided by a control algorithm embedded in the IoT platform. The task of the control algorithm will be to set the right duty cycle so that the indoor temperature matches the set-point temperature. The AC energy consumption is derived from a sample of the temperature curve when ON/OFF occurs on the compressor. The room temperature will decrease if the compressor is turned ON as the curve shown in Figure I. The temperature curve as a function of time can be approximated by

$$T_{ON}(t) = T_{Low} + \Delta e^{-\beta_{k,n}\left(\frac{t}{t_{ONC}-t}\right)} \tag{1}$$

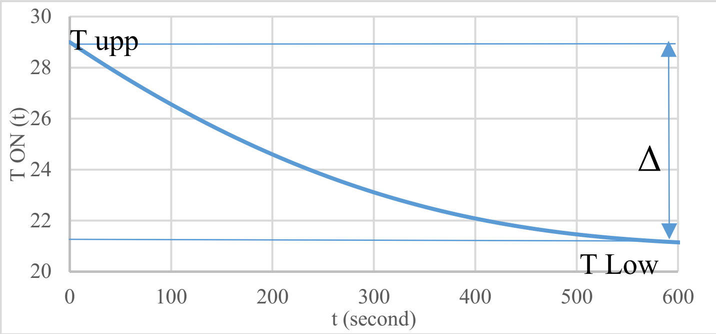

Fig. 1. Screenshot of room temperature when compressor is switched ON

tONC is the time constant when *TON*(*t*) = *TLow*. Furthermore, the duration of time required by the compressor to lower the interior temperature until it reaches the lower limit temperature level (*TLow*) can be formulated by

$$t_{k,n}^{in-ON} = \frac{t_{ONC}}{\left(-\beta_{k,n}\left(\ln\left(\frac{T_{ON}(t)-T_{LOW}}{\Delta}\right)\right)^{-1}\right)+1} \tag{2}$$

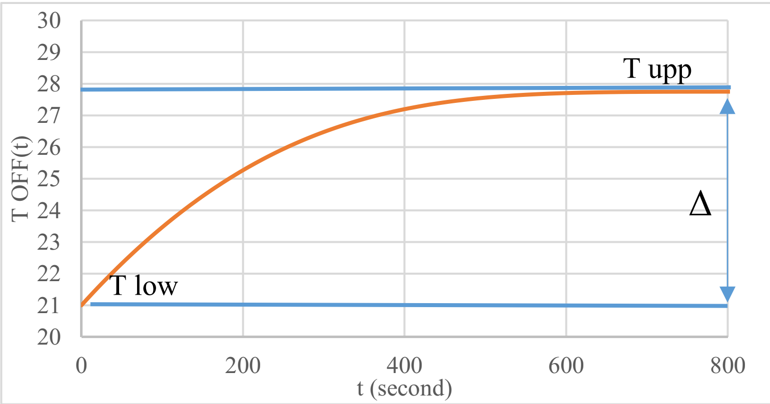

Fig. 2. Screenshot of room temperature when compressor is switched OFF

The temperature curve as a function of time in Figure 2 can be approximated by

$$T_{OFF}(t) = T_{Low} + \Delta(1 - e^{-\lambda_n(\frac{t}{t_{OFC}-t})}) \tag{3}$$

tOFC is the time constant when *TOFF*(*t*) = *Tupp*. The duration of the compressor OFF time that causes the room temperature to rise gradually until it reaches the upper *Tupp* limit can be defined by

$$t_n^{in-OFF} = \frac{t_{OFC}}{\left(-\lambda\left[ln\left(1-(\frac{T_{OFF}(t)-T_{Low}}{\Delta})\right]^{-1}\right)+1} \tag{4}$$

In (4) above shows that if TLow is set further away from the surface of the thermal equilibrium of the room, the duration of the compressor OFF time will be shorter as a result, the air conditioner will consume more energy. If we look at Figure II, when the temperature gets lower, the value of λ gets bigger causing the value of the OFF time in (4) to get smaller. This shows that if the temperature is getting lower due to the AC being turned on, the thermal potential of the room temperature is getting bigger to get to the surface of thermal equilibrium. One duty cycle may not be the same as another duty cycle depending on the six parameters in the duty cycle equations (2) and (4). Furthermore, the energy consumption of the AC consisting of several cycles during which the AC is turned on can be formulated by

$$E_{Cycle(n)} = \sum_{n=0}^{n}(E_{ON,k,0} + E_{ON,k,n} + E_{OFF,n}) \tag{5}$$

Where;

$$E_{ON,k,0} = \overline{P}_{ON,k,0} \frac{t_{ONC}}{\left(-\beta_{k,0}\left(ln(\frac{T_{ON}(t)-T_{Low}}{\Delta_0})\right)^{-1}\right)+1} \tag{6}$$

$$E_{ON,k,n} = \sum_{n=1}^{n} \overline{P}_{ON,k,n} \frac{t_{ONC}}{\left(-\beta_{k,n}\left(ln(\frac{T_{ON}(t)-T_{Low}}{\Delta})\right)^{-1}\right)+1} \tag{7}$$

$$E_{OFF,n} = \sum_{n=1}^{n} \overline{P}_{OFF,n} \frac{t_{OFC}}{\left(-\lambda\left[ln\left(1-(\frac{T_{OFF}(t)-T_{Low}}{\Delta})\right]^{-1}\right)+1} \tag{8}$$

Energy consumption in this study can be modeled with the pattern shown in Figure 3. When the AC compressor is turned ON, the indoor temperature will decrease with a slope value of β. The β coefficient is the value of the AC performance coefficient (μ) minus the value of the building's thermal transfer coefficient and the heat capacity contained by the elements and the walls of the room (λ). When the compressor is OFF, the room temperature change index value is only determined by the thermal transfer coefficient of the building and the heat capacity contained by the elements and the walls of the room (λ). The room temperature function describing several ON/OFF cycles can be derived from (7) and (8) to

$$T(t) = (T_{Low} + \Delta e^{-\beta_{k,n}(\frac{t}{t_{ONC}-t})})\delta + (T_{Low} + \Delta(1 - e^{-\lambda_{k,n}(\frac{t}{t_{OFFC}-t})})1 - \delta \tag{9}$$

Delta Dirac (δ) indicates compressor ON/OFF control. The value of δ is equal to 1 if the compressor is ON. On the other hand, will be 0 if the compressor is turned OFF. The first right term in (9) will run if the compressor is ON, while the second right term will be zero. However, if the compressor is turned OFF, the opposite condition will happen.

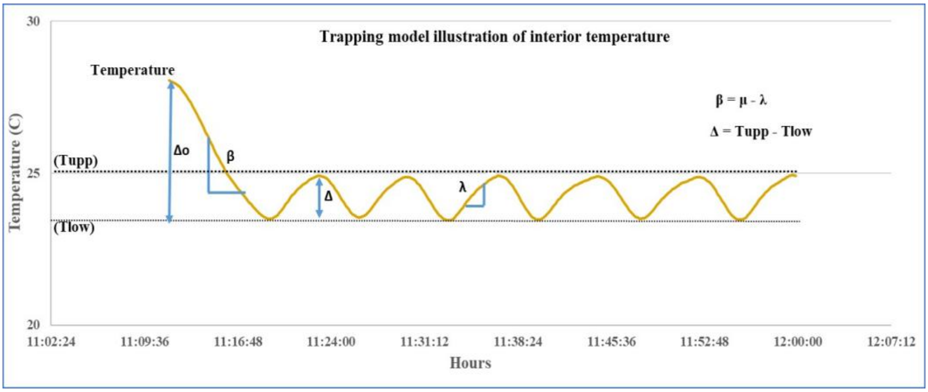

Fig. 3. Temperature relaxation model on AC energy control

Figure 3 shows that $Tupp = Ts + 1/2\Delta$ and $TLow = Ts - 1/2\Delta$ which if substituted in (7) and (8) will give AC energy consumption which is affected by the temperature set-point indicated by

$$E_{ON,k,n} = \sum_{n=1}^{n} \bar{P}_{ON,k,n} \frac{t_{ONC}}{\left(-\beta_{k,n}\left(ln\left(\frac{T_{ON}(t)-T_{Low}}{2(T_S-T_{upp}-\Delta)}\right)\right)^{-1}\right)+1} \tag{10}$$

$$E_{OFF,n} = \sum_{n=1}^{n} \bar{P}_{OFF,n} \frac{t_{OFC}}{\left(-\lambda\left[ln\left(1-\frac{T_{OFF}(t)-T_{Low}}{2(T_S-T_{upp}-\Delta)}\right)\right]^{-1}\right)+1} \tag{11}$$

λ and β are parameters that depend on indoor and outdoor environmental conditions. These two parameters become obstacles in determining the duty cycle of the compressor. To overcome these obstacles, the fuzzy hysteresis algorithm is the main strategy method for controlling AC energy consumption and room temperature. Controlling AC energy consumption and room comfort through a hysteresis approach is to trap the indoor temperature to keep it fluctuating around the set point temperature which is set from the parameters Ts and Δ contained in (10) and (11). The variation of these two parameters will be tested how much their contribution to AC energy savings and the achievement of room comfort refers to the ASHRAE standard. .

2.2 Internet of Things

The best tool in AC performance investigation and engineering is the Internet of things (IoT). The standard IoT infrastructure model has been described in four major groups i.e. The sense and control group is to measure the physical parameters of their environment and act as controllers. The device can consist of sensors, actuators, embedded controllers or certain objects and edge gateways [9 - 11]. Basic examples of these objects include thermostats and heating, ventilation and air conditioning (HVAC) monitoring and control systems [12 - 14]. Furthermore, visualize and response groups is to display information to the user (user interface). The devices are usually PCs, smartphones, and laptops. The user interface is in the form of a web interface and applications that are embedded in android. Big-data group is to get information in making decision. Intelligent and analysis as a rule engine to process data from various sensors (big-data) as well as meaning data to extract analytical knowledge and its consequences. The output of this group is a decision in the form of control parameter values. The communication protocols for the interaction of the three groups above use the messaging queuing telemetry transport (MQTT) [15 - 18] and Hypertext Transfer Protocol (HTTP) request [19]. This study refers to[7, 20, 5] who have combined physics concepts with the internet of things for energy conservation in AC. They also has developed AC control using fuzzy logic and PID in an intelligent AC system. The three studies above still need to be developed for specific targets, so this research is presented for convenience purposes set by ASHRAE standards.

3 Experimental Design

3.1 Designing of Point Control of Internal AC

The type of air conditioner used in this study is split AC. In general, split air conditioners have a micro-controller equipped with four sensors as input variables for the control algorithm, the output of which is two drivers that will control the three components of the air conditioner consisting of a compressor, condenser, and evaporator.

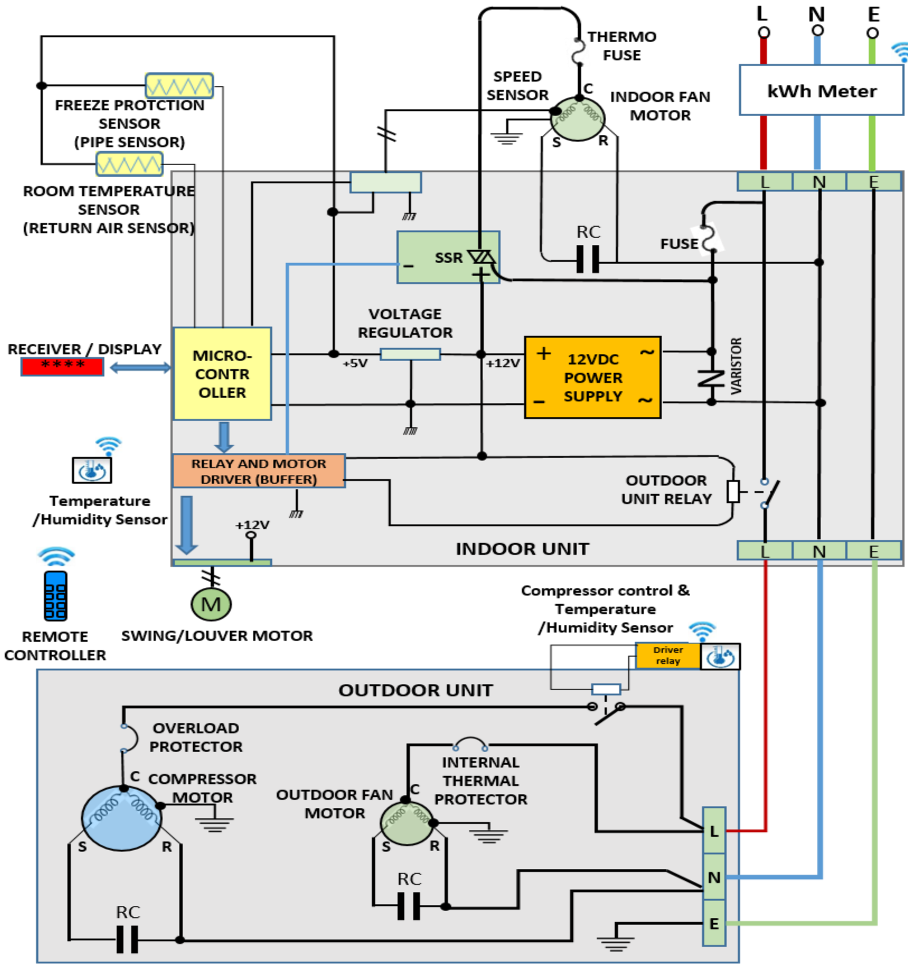

Fig. 4. AC control point internal line

The four sensors consist of a temperature sensor, a freeze sensor, an evaporator fan motor speed sensor and an infrared sensor. The paths and points that will be controlled to save AC energy can be seen in Figure 4. It shows the placement of additional hardware such as kWh meter, indoor/outdoor temperature sensor and compressor control actuator. The indoor temperature sensor must be placed in a room that can represent the actual room temperature. Meanwhile, the additional hardware for compressor control is connected in series with the control of the main compressor of the indoor unit. This means that the compressor works under the influence of both indoor and outdoor temperature. This split AC operational logic is designed to be AND logic. This means that the ON decision will occur if the additional control of the compressor and the main control of the compressor in the AC indoor unit are both in the HIGH state. When the outside temperature is higher than the set-point temperature and the indoor temperature is far below the set-point, the main control of the compressor in the indoor air conditioner unit will be standby in the ON state while ON/OFF with a certain duty cycle will be carried out by additional control. On the other hand, when the outside temperature is low and the inside temperature is higher than the normal temperature (warm), then the additional control of the compressor will standby in the ON state while ON/OFF with the AC's default duty cycle will be carried out by the main compressor control on the indoor AC unit as shown in Figure IV above. Additional compressor control will be guided by intelligence on the IoT platform embedded control algorithm. The IoT system built in this study follows a standard pattern that is realized in controlling AC energy consumption and room comfort as shown in Figure 5.

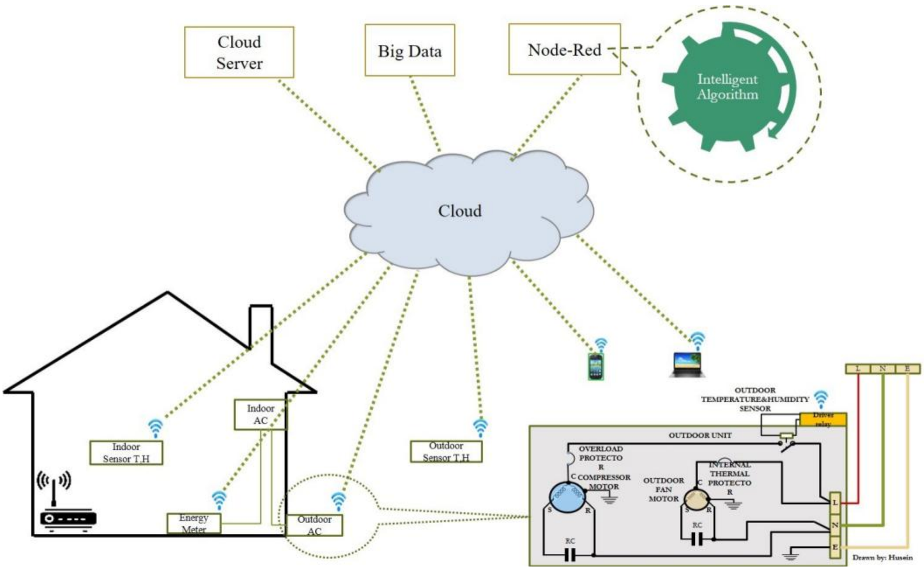

Fig. 5. Architecture of IoT for experiment in AC

Figure 5 explains the simple IoT implementation system in this study consists of several parts with the following details: four sensor and actuator nodes, AC, Cloud, Middleware and Cloud server. All components in this IoT system will be explained in detail in appendix B starting from the Kwh meter, sensor and actuator circuit as well as the intelligent embedded in the node-red.

3.2 Designing of Hysteresis Control Algorithm

The hysteresis approach to control the compressor is based on the temperature relaxation model in Figure 3 using equations (10) and (11) wherein, energy consumption can be guided through the variables Ts and Δ. The two variables will give the upper limit temperature (Tupp) and the lower limit temperature (Tlow). When the indoor temperature is included in the logic function, the output of the logic will give the compressor

ON and OFF commands. The hysteresis model for controlling the compressor duty cycle can be done by adjusting the combination of Ts and values of Δ. This hysteresis algorithm will be embedded in the function node in node-red. Data from sensors and from set-points will be subscribed by the MQTT node then each data will be parsed and displayed on the dashboard. The temperature set-point data for the lower and upper limits will always be stored in the setting memory. Then when the indoor temperature data enters, it is executed directly by the logic function. If the indoor temperature is greater than or equal to the upper limit temperature set-point, the function will issue an ON command, if the indoor temperature is less than or equal to the lower limit temperature set-point then the function will issue an OFF command. The ON and OFF commands will be published by the MQTT Node with a unique topic so that it can be subscribed by the compressor control actuator node. For more details, it can be seen from the program flowchart as shown in Figure 6. Variation of Δ and Ts values in the hysteresis algorithm will be guided by fuzzy logic to follow the ASHRAE standard embedded in the intelligent control system.

3.3 Design Fuzzy Role ASHRAE Standard of Hysteresis Control Algorithm

The hysteresis model for controlling the compressor duty cycle can be done by adjusting the combination of Ts and values of Δ. This hysteresis algorithm will be embedded in the function node in node-red. Data from sensors and from set-points will be subscribed by the MQTT node then each data will be parsed and displayed on the dashboard. The temperature set-point data for the lower and upper limits will always be stored in the setting memory. Then when the indoor temperature data enters, it is executed directly by the logic function. If the indoor temperature is greater than or equal to the upper limit temperature set-point, the function will issue an ON command, if the indoor temperature is less than or equal to the lower limit temperature set-point then the function will issue an OFF command. The ON and OFF commands will be published by the MQTT Node with a unique topic so that it can be subscribed by the compressor control actuator node. For more details, it can be seen from the program flowchart as shown in Figure 6. Variation of Δ and Ts values in the hysteresis algorithm will be guided by fuzzy logic to follow the ASHRAE standard embedded in the intelligent control system.

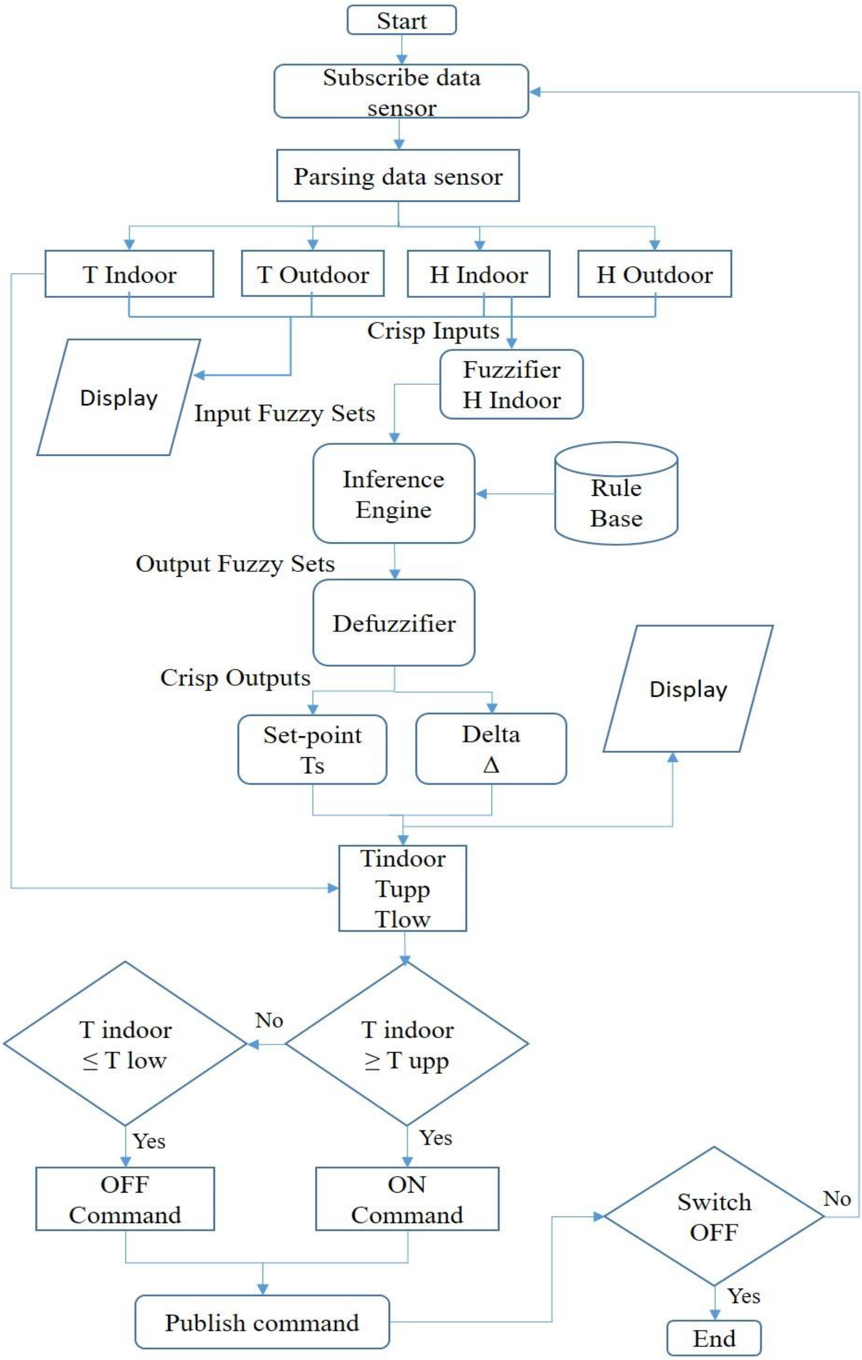

Fig. 6. Compressor control hysteresis algorithm in the middle-ware guided by Fuzzy Logic

The development of the standard ASHRAE hysteresis algorithm can be done based on the characteristics of the ASHRAE curve. These characteristics become the set-point range and indoor temperature fluctuations.

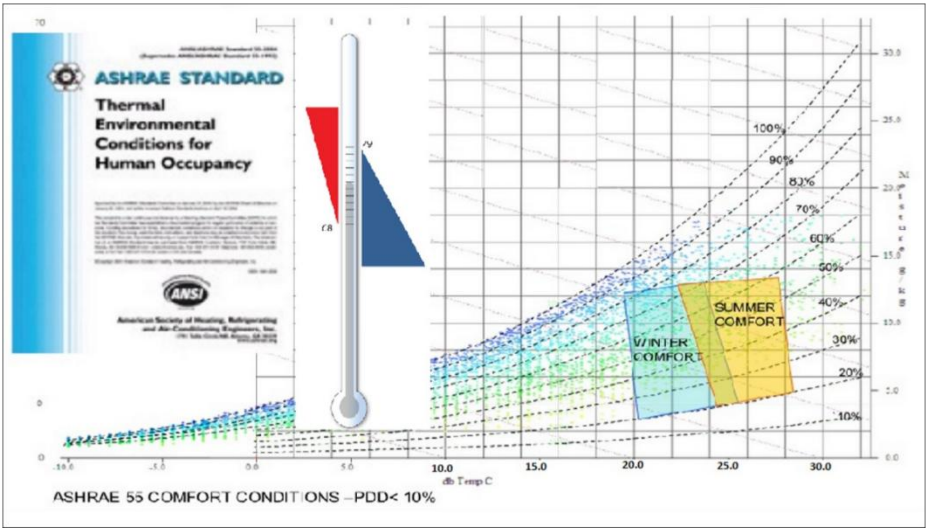

Fig. 7. ASHRAE standard occupant comfort curve (source: ASHRAE 55 Comfort conditions)

Furthermore, the ASHRAE standard comfort curve is made in the form of a Fuzzy Logic rule that will fuzify indoor humidity whose output is a set-point value and room temperature fluctuations that span the ASHRAE standard comfort area. The comfort curve of the ASHRAE version above can be made in the form of a rule engine hysteresis Table I. It should be noted that the comfort in the ASHRAE curve refers to summer because this research was conducted in Indonesia, which has a summer season throughout the year. From the ASHRAE curve, we are given a comfortable temperature range (Tlow -Tupp) for each humidity level. Humidity of 75% to 100% and from 0% to 19% does not fall within them comfort area. However, because the purpose of this study is to optimize energy, fuzzy rules for boundaries that are not included in the area are made special rules that are the same as humidity which is closer to the limit of numbers that fall within the comfort range. Thus, we can consider that if we take a small value of the temperature relaxation will increase the compressor ON/OFF frequency so that it is not good for the air conditioner. On the other hand, the given value of Δ should not be too large for convenience reasons. The ASHRAE standard is formed as in Table I. Table I is the result of a modification of appendix Table A1 where table A1 is a conversion of the numbers from the comfort ASHRAE curve in the summer season. Because this research was conducted in Indonesia, where the average weather throughout the year is similar to the summer season on the European continent. The Table became rule base that will be given to the hysteresis algorithm control of AC compressor.

Table 1. Fuzzy rule hysteresis which refers to ASHRAE standard.

Humidity (%)	Tupp(^{0}C)	Tlow(^{0}C)	Δ(^{0}C)	Ts(^{0}C)
100	23.5	22.75	0.5	23
95	23.5	22.75	0.5	23
90	23.5	22.75	0.5	23
85	23.5	22.75	0.5	23
80	23.5	22.75	0.5	23
75	23.5	22.75	0.5	23
70	23.5	22.75	0.5	23
65	24	23	1	23.5
60	24	23	1	23.5
55	24	23	1	23.5
50	24	23	1	23.5
45	24	23	1	23.5
40	24	23	1	23.5
35	24	23	1	23.5
30	24.5	23.5	1	24
25	24.5	23.5	1	24
20	24.5	23.5	1	24
15	24.5	23.5	1	24
10	24.5	23.5	1	24

The standard ASHRAE hysteresis algorithm is designed as the usual hysteresis algorithm but it was developed where the set-point (Ts) and temperature fluctuation (Δ) are guided by additional fuzzy rules derived from the ASHRAE version of the comfort curve shown in Figure 8. The algorithm will be embedded in the cloud as an intelligent control system to guide the operation of the AC system with the following pattern

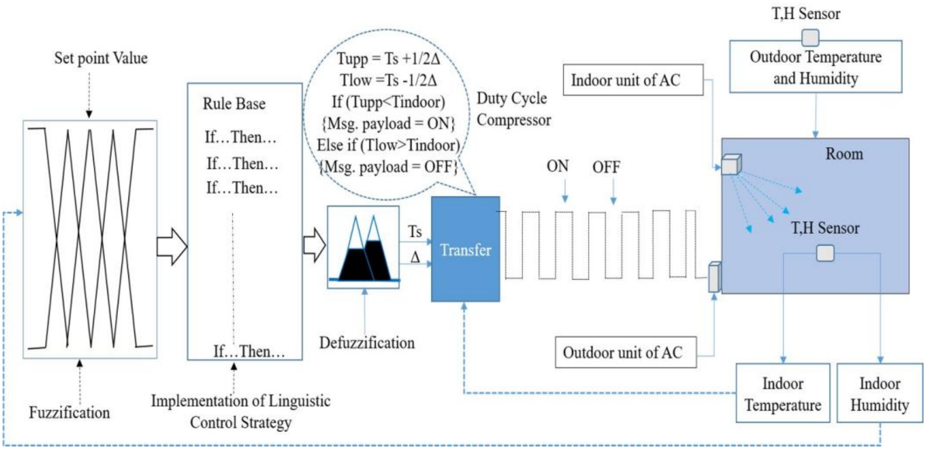

Fig. 8. Hysteresis mechanism of action according to ASHRAE standard comfort

Figure 8 shows that the room humidity sensor will publish humidity data and be subscribed by the Fuzification function, then the humidity value will enter the rule base which contains the rules in table I. The output from the rule base is in the form of Ts and Δ values. These two values, together with the indoor temperature, are entered into a logic function whose output is an ON and OFF decision. The decision will be published and subscribed by the outdoor AC unit to turn on and turn off the compressor as a source of room temperature activation

4 Results and Discussion

4.1 Effect of Outdoor Temperature Towards Energy Consumption

Hysteresis compressor control is referred to in equations (10) to (11) where changes in the set-point temperature (TS) value with the desired fluctuating temperature (Δ) will have a different impact on AC energy consumption. The additional control of the compressor is to vary the range of set-point temperature values (TS) with a fluctuating value of Δ. The first profile of the contribution of this hysteresis control algorithm can be seen in the AC energy consumption curve that applies the values (Δ = 0.4 and TS = 23,8). This experiment shows that the AC energy consumption is not only determined by changes in the limit value (Δ) but is highly dependent on the outside temperature which is difficult to control it. The value of the thermal transfer coefficient (λ) and the value (Δ) has given a change in the energy efficiency of the air conditioner. This corresponds to (10) to (11) above. The coefficient λ describes the amount of heat entering the room. In this study, the value of λ was contributed more by the outside temperature. This can be seen clearly the behavior of AC energy consumption which is influenced by outside temperature in Figure 9.

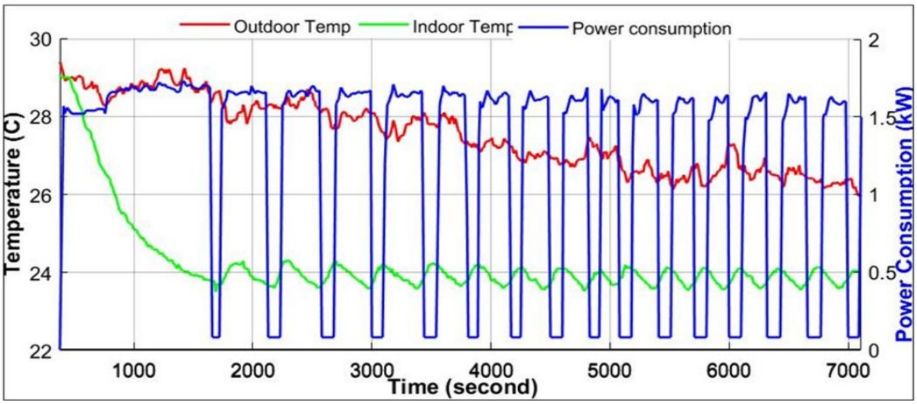

Fig. 9. Performance of AC energy consumption due to the influence of outside temperature

The Figure 9 shows the compressor ON pulse width decreases significantly as the outside temperature decreases while the indoor temperature remains at a given set-point

Ts and fluctuates Δ. To see the effect of outside temperature which is represented by the value of λ in equations 10 and 11, it is shown in Figure 10. The curve shows that if the outdoor temperature increases by 1^0C, the control algorithm will increase the time of compressor ON by 15.27%, meaning that the higher the outside temperature, the AC energy consumption will also increase.

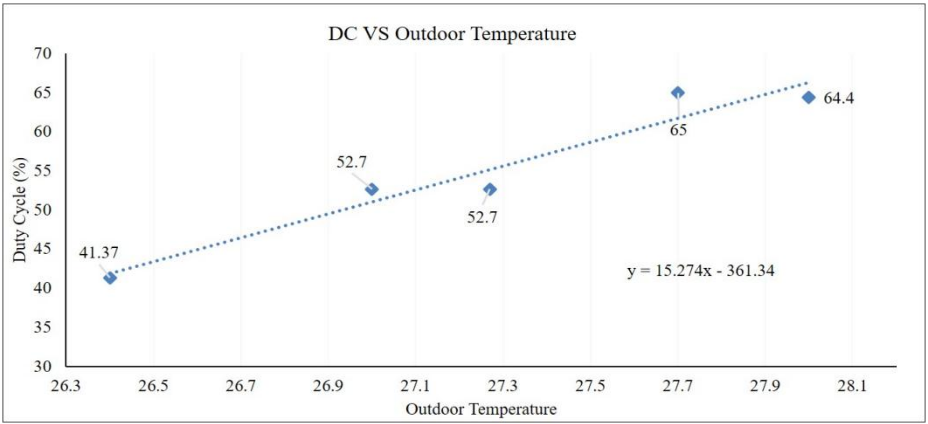

Fig. 10. Effect of outdoor temperature on duty cycle

4.2 Effect of Ts and Δ on AC Energy Consumption on Hysteresis

This experiment was conducted to see the effect of changing the set-point on the Duty Cycle value at a fixed value of Δ.

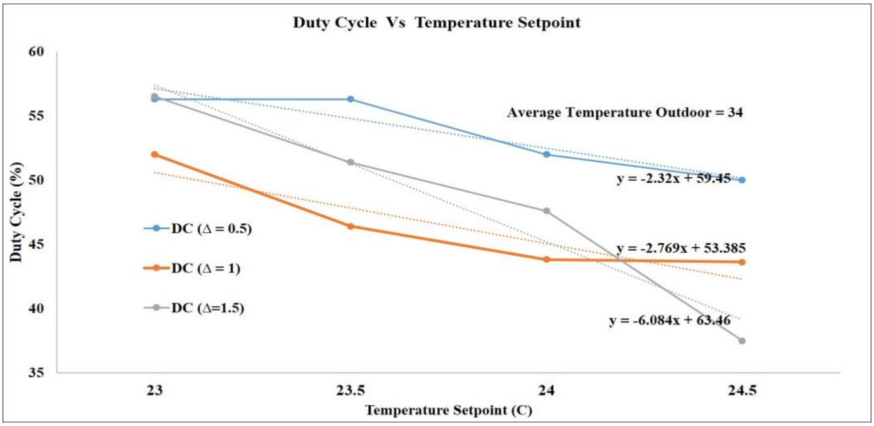

Fig. 11. Duty Cycle Profile at different Set point Ts and Δ

The first cycle was carried out by setting Δ = 0.5 at an outside temperature of $34,51^0$C. Set-point value ranges from 23^0C to $24,51^0$C with 0.5 steps. Duty cycle at different set-points from the results of this experiment can be seen in Figure 11. It shows that at the setting Δ = 0.5, the maximum value of Duty Cycle is 56.3% at set-point 23 ^{0}C and the minimum at set-point 24.5oC is 50%. Savings in this setting are at least 43.7% and have the opportunity to reach 50% at a set-point of 24.5 ^{0}C even though the outside temperature is so high. Every 1oC increase in set-point will reduce energy consumption by 4.64%. This value is superior to the decrease in consumption from the AC's own set-point control which only reaches 2%. Furthermore, the second cycle is carried out by setting the value $\Delta = 1$ at an outside temperature of 34 ^{0}C. Variation range of set-point values from 23 ^{0}C to 24.5 ^{0}C with 0.5 steps. The profile of Duty Cycle values at different set-points at setting $\Delta = 1$. The maximum Duty Cycle value is 52% at set-point 23 ^{0}C and minimum Duty Cycle is 43.6% at set-point 24.5^{0}C. Savings in this setting are at least 48% and it has the opportunity to reach 56.4% at a set-point 24.5 ^{0}C even though the outside temperature is also so high. Every 1^{0}C increase of the set-point will reduce energy consumption by 5.54%. This value is superior to decrease consumption from the default set-point control of the AC which only reached 2% and the decrease in consumption at the setting $\Delta = 0.5$ which reached 4.64%. The third cycle is carried out by setting the value $\Delta = 1.5$ at an outside temperature of 33,4^{0}C. Variation range of set-point values from 23 ^{0}C to 24.5 ^{0}C with 0.5 steps. The profile of Duty Cycle values at different set-points at setting $\Delta = 1,5$ shows the maximum Duty Cycle value is 56,52 % at set-point 23 ^{0}C and minimum Duty Cycle is 37,5 % at set-point 24.5 ^{0}C. Savings in this setting are at least 43% and it has the opportunity to reach 62,5 % at a set-point 24.5 ^{0}C even though the outside temperature is also so high. Every 1^{0}C increase of the set-point will reduce energy consumption by 12,6%. This value is superior to decrease consumption from the default set-point control of the AC which only reached 4,64% and the decrease in consumption at the setting $\Delta = 1$ which reached 5.54%.

4.3 ASHRAE Standard Hysteresis Control Algorithm Performance

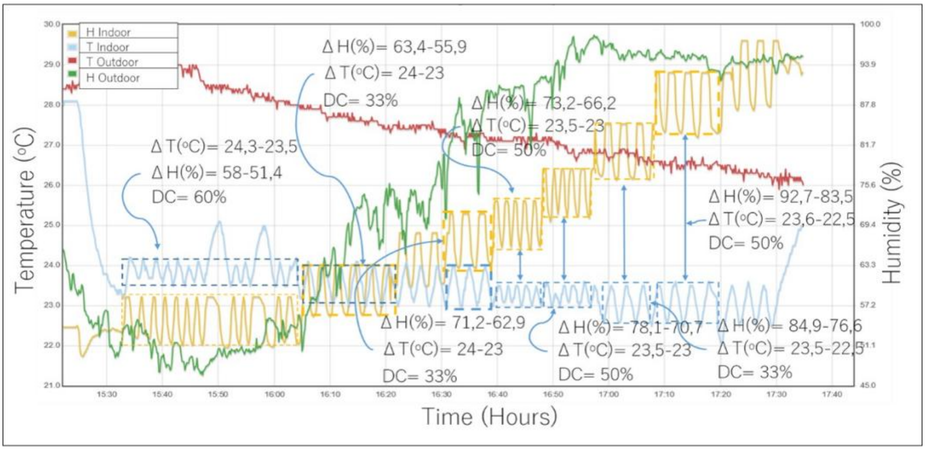

Fig. 12. Performance of the ASHRAE standard hysteresis algorithm

The performance of the ASHRAE standard hysteresis algorithm is shown in Figure 12. Energy consumption can be seen from the value of the duty cycle. The duty cycle value for each humidity level is clear that in almost all conditions of indoor humidity levels, the air conditioner achieves savings of ± 50%. Thus, the ASHRAE hysteresis algorithm can meet a fairly good efficiency. Figure 12 shows that every change in room humidity will be followed by a change in set-point and temperature fluctuations following the ASHRAE comfort curve. This is an indicator that this algorithm works in perfect condition.

5 Conclusion and Future Work

The author has developed an IoT-based energy conservation system and its application to AC where the three aspects of energy conservation, both monitoring, analysis, and control intelligence can be carried out simultaneously and in real time, previously only using simulation software. The set-point control algorithm built by AC through the behavior of indoor temperature and AC energy consumption under the influence of outdoor conditions is more detailed than the behavior of AC energy consumption investigated by N. Wang et al. 2013 has been identified. This research has succeeded in developing a physics model that underlies the temperature relaxation algorithm through compressor control which produces stable performance and can overcome the weaknesses of the original of its own AC set-point control algorithm, both in savings and in comfortable. In terms of savings, hysteresis control can save AC energy consumption by 50% when the AC default control algorithm cannot save it. In terms of comfort, hysteresis control can overcome excessive cooling and is able to achieve set-point temperatures. From the overall results obtained in this study are in accordance with the concept of the theory that was built. The hysteresis algorithm built in this study has met the standard occupant comfort according to ASHRAE with an average savings of 50%.

Abbreviations

The following abbreviations are used in this manuscript:

a. IoT = Internet of Things
b. MQTT = Messaging Queuing Telemetry Transport
c. HTTP = Hypertext Transfer Protocol
d. HVAC = Heating, Ventilation and Air Conditioning
e. ASHRAE = American society heating, refrigeration, air conditioner engineer
f. $\Delta 0$ = Room Temperature Characteristic
g. β = Temperature change index when the compressor is ON
h. λ = Temperature change index when the compressor is OFF
i. μ = AC performance coefficient
j. $T_{ON}(t)$ = Room temperature function when the compressor is ON
k. T_{LOw} = The lower limit of room temperature is until the compressor is almost turned OFF
l. Δ = Indoor temperature fluctuation limits when the compressor is turned on and off
m. $\beta_{k,n}$ = The value of β at The k (th) setpoint and n (th) cycle

n. t = Time in second
o. Tupp = The upper limit of room temperature until the compressor is almost ON
p. k,n = The *k* (*th*) setpoint and *n* (*th*) cycle
q. DC = Duty Cycle
r. T*OF F*(*t*) = Room temperature time function when the compressor is turned OFF
s. E*cycle*(*n*) = The energy consumed by the AC during n cycles
t. E*ON*,*k*,0 = Energy consumed by the AC in the initial cycle
u. E*ON*,*k*,*n* = Energy consumed by the AC in the next cycle until the nth cycle (ON)
v. E*OFF*,*n* = Energy consumed by the AC in the next cycle until the nth cycle (OFF)
w. P*ON*,*k*,0 = AC Power Consumption when the compressor is ON at set-point to k and initial cycle
x. P*ON*,*k*,*n* = AC power consumption when the compressor is ON at set-point to k and n cycles
y. P*OFF*,*k*,*n* = AC power consumption when the compressor is OFF at set-point to k and n cycles

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