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Sustainability of Energy Conservation in HVAC System Using Fuzzy Logic

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Abstract

Nowadays, air-conditioning systems are installed in buildings to provide a healthy and comfortable environment for the occupants. However, it will consume a large amount of energy resulting in an expensive cooling cost in the building. This paper presents an approach to minimize the energy consumption of the heating, ventilation and air conditioning (HVAC) system. The main objective is to provide a solution to reduce the energy consumption of a house air system using fuzzy logic by controlling the expansion valve of the air conditioner. The membership functions of fuzzy logic consisting of two inputs and one output were used as a method to control the output temperature of the system. The output shows a reduction in the cooling cost of the HVAC system in a building.

1. Introduction

Recent studies have shown that buildings are responsible for around 40% of the world's energy consumption and nearly 33% of greenhouse gas emissions [1]. In a building, the largest proportion of electrical power consumption at approximately 60% is attributed to heating, ventilation and air conditioning (HVAC) [2]. The changing global climate has led to an increase in demand for electricity to power air conditioning systems. To address this issue, various systems have been employed to minimise energy consumption resulting from the rising use of comfort cooling or air conditioning. These include controlling the building's thermal mass by modifying the indoor temperature set point [3].

There have been several studies regarding the utilization of fuzzy logic to control the basic components of HVAC system such as the condensing coil, expansion valve, evaporating coil, and compressor [4]. These studies demonstrate that the implementation of a fuzzy logic controller in the HVAC system of a building can result in reduced energy consumption and cost savings [5]. In previous research, a fuzzy logic controller was utilized to regulate the HVAC basic unit's compressor by managing the changing of refrigerant [6]. These findings demonstrate that incorporating the fuzzy logic controller into the system will enhance its energy conservation and reduce cost of energy consumption. The significance of this study is that it showcases the potential benefits of lowering a building's cooling expenses and increasing awareness on the impact of minimizing energy consumption.

The objective of this paper is to conduct an energy conservation analysis on HVAC model controlled by a fuzzy logic controller. The simulation was performed to explore the impact of the fuzzy logic controller on the house temperature as it varied in response to the surrounding temperature. The fuzzy logic controller was designed with two inputs which are the temperature error and error of temperature variation; and one output air flow variable.

Both input and output values represent 9 membership functions. In addition, all necessary information was recorded to analyze the cooling cost improvement of the HVAC system which is 24.81% during 72 hours of operation.

2. Methodology

2.1 HVAC Operating System

The vapour refrigerant (typically R134a) from the air conditioning system was produced by the condenser as shown in Fig. 1. The condensing coil was then used to release the heat from the refrigerant so that it turned back into a cool fluid. The flow of the cool fluid to the evaporator was then controlled by the expansion valve according to the cooling demand. At the evaporator coil, the fluid changed into sub-cooled vapour with low pressure and temperature. Finally, the process was repeated again as the vapour returned to the compressor.

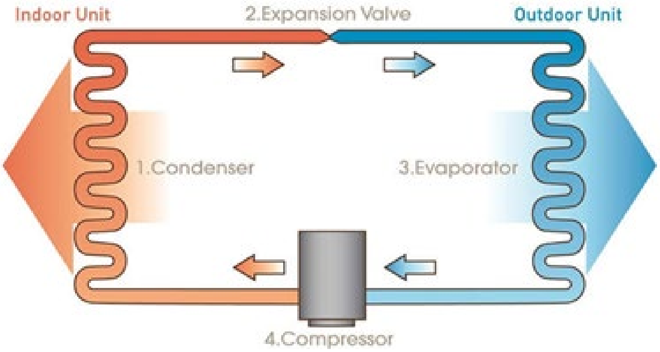


Fig. 1 *HVAC refrigeration cycle*

2.2 Principle of Fuzzy Logic Controller

Fig. 2 shows the basic principles of the fuzzy logic operating subsystem. The fuzzification block transforms the input data into a fuzzy data set and the fuzzy inference engine operates with fuzzy rules to regulate the expansion valve. The target output temperature can be achieved by controlling the expansion valve. Finally, the defuzzification block is used to transform the fuzzy set into the desired output temperature of the HVAC system.

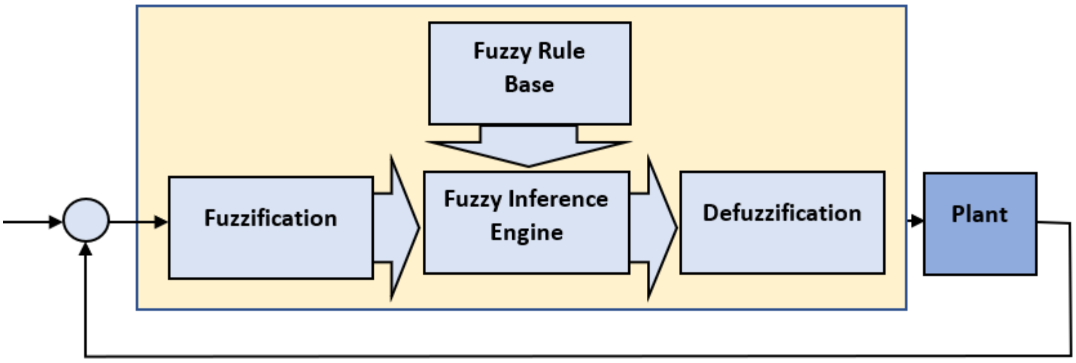


Fig. 2 *Operating principle of fuzzy logic subsystem*

2.3 Fuzzy Logic Implementation in HVAC

This section will discuss the implementation of fuzzy logic to control the temperature carried out in the Simulink software. Fig. 3 shows that the system is set to the desired output temperature known as the set point temperature. The set point will then be subtracted from the temperature variation of the house (Tindoor) to produce an error temperature which will be sent to the thermostat and memory. In the thermostat, the temperature error determines whether to activate or deactivate the air-conditioning blower automatically. The blower will activate when the thermostat command is 1. If the command is 0, then the blower will deactivate. Meanwhile, the temperature error is also used by memory to create temperature variations corresponding to indoor temperature changes. The fuzzy logic controller was designed to regulate the expansion valve of the air-conditioning unit to manage the flow of gas to the cooler switch.

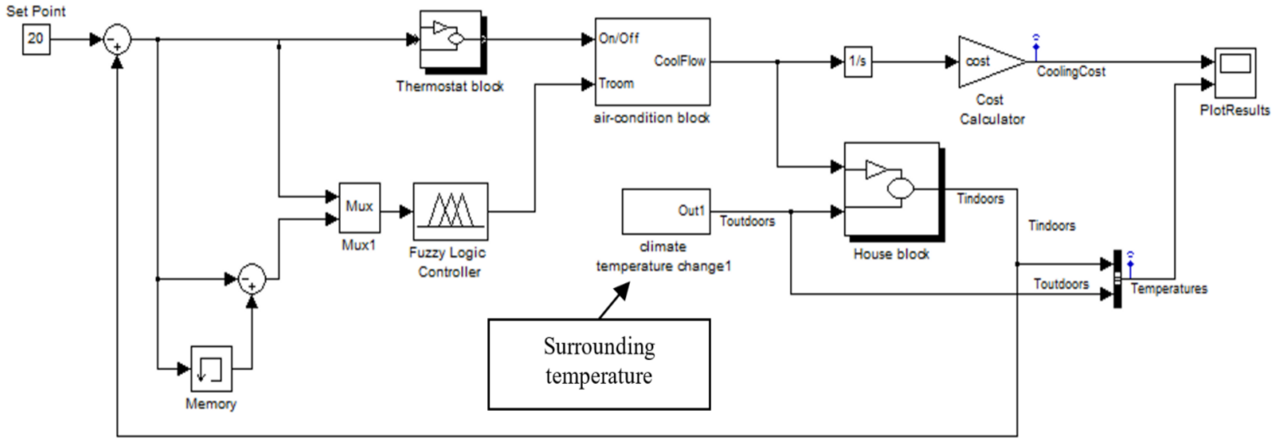


Fig. 3 *Improved model of HVAC considering fuzzy logic controller*

2.3.1 House parameter estimation

The initial stage involves calculating the insulation of a house. This is achieved by entering the thickness of the walls and windows along with the thermal conductivity of the walls and glass in Fig. 4. Eq. (1) to Eq. (3), demonstrate the derivation of the equivalent thermal resistance, R_{eq}, obtained from the aforementioned information.

$$R_{wall} = \frac{L_{wall}}{K_{wall} \times H_{wall}} \tag{1}$$

$$R_{window} = \frac{L_{window}}{K_{window} \times H_{window}} \tag{2}$$

$$R_{eq} = \frac{R_{wall} \times R_{window}}{R_{wall} \times R_{window}} \tag{3}$$

where, L_{wall} = Wall length, L_{window} = Window length, H_{window} = Window height, H_{wall} = Wall height, W_{wall} = Wall width, K_{window} = Thermal conductivity of window, and K_{wall} = Thermal conductivity of wall.

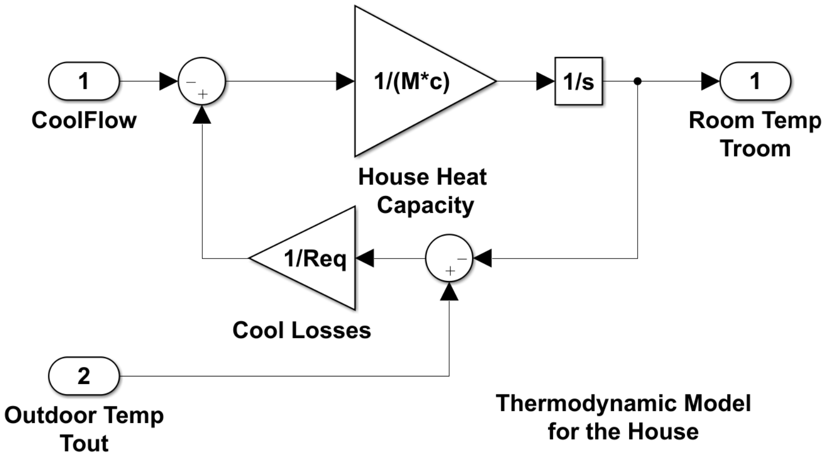


Fig. 4 *House subsystem*

Once R_{eq} has been calculated, other parameters need to be defined such as the specific heat capacity of air (c), the air air-conditioning output temperature (Taircond), the air flow rate (Mdot), the density of air at sea level (dens Air), the total internal air mass (M) and the initial indoor temperature (TinIC). All of the obtained parameters are then applied in the system diagram of HVAC as shown in Fig. 3.

2.3.2 HVAC system

There are five primary subsystems within the HVAC system which are the thermostat subsystem, air-conditioner subsystem, surrounding temperature subsystem, fuzzy logic controller subsystem and house subsystem. Fig. 3 present the overall cooling house model in Simulink software. The five main subsystems will now be discussed in detail.

2.3.2.1 Thermostat subsystem

Fig. 5 illustrates the thermostat subsystem, comprising a relay component with an ON and OFF switch point. This point operates in correlation with the input temperature error (Terr) to control the blower, which regulates the flow of cool air referred to as CoolFlow. This air flows into the interior of the air-conditioning system as depicted in Fig. 6. The blower will be turned On when the relay signal shows an output of "1" and it will turn OFF when the relay shows an output of "0".

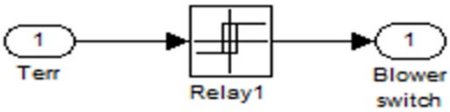


Fig. 5 *Thermostat subsystem*

2.3.2.2 Air-conditioning subsystem

The air-conditioning subsystem controls the flow of cool air into the house. In Fig. 6, the result between the room temperature (Troom) and the cooler air temperature (Taircond) will be multiplied by the product of the air-flow rate (Mdot) and the specific heat capacity of air (c). This process occurs in the CoolGain block which represents a mathematical model for the expansion valve. This expansion valve regulates the flow of refrigerant gas to the cooler switch and the blower is controlled by the thermostat.

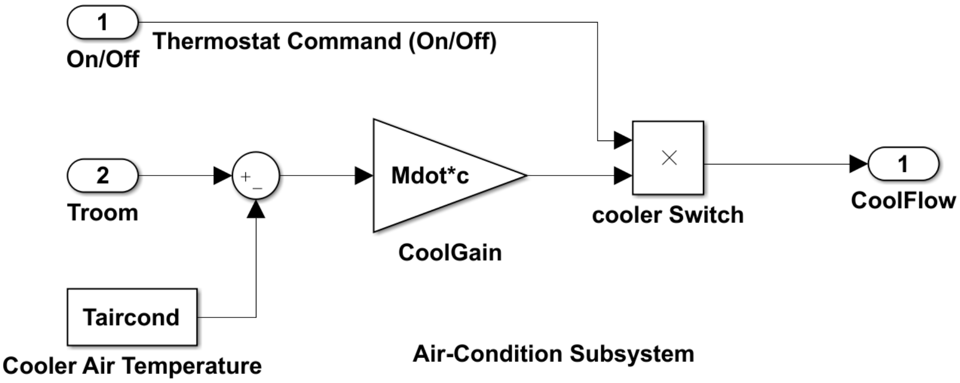


Fig. 6 *Air-conditioning subsystem*

2.3.2.3 Surrounding temperature subsystem

Fig. 7 shows the model of the surrounding temperature subsystem that generates an outdoor temperature for the system. The subsystem utilises a timer to produce an output wave of outdoor temperature based on Clock1. If the timer has a value of 24, the output will depend on the value of α. If the timer has a value of 24 to 48 hours, the output will be β. If the timer has a value of 48 to 72 hours, the output will be γ. Eq. (4) illustrates the output as a function of the temperature corresponding to the timer selection.

$$f(\alpha,\beta,\gamma)=\begin{cases}\alpha, & \text{if } t\le 24\\ \beta, & \text{if } 24\le t\le 28\\ \gamma, & \text{if } 48\le t\le 72\end{cases} \tag{4}$$

2.3.2.4 House subsystem

The housing subsystem is responsible for measuring the outdoor temperature for cooling losses, the cool air flow (CoolFlow), and the housing cooling capacity according to the initial parameter that is used for the cooling process.

In Fig. 4, the difference between the outdoor temperature and the house temperature is calculated to determine the exact temperature that the air-conditioning system needs to provide. Eq. (5) present the equation to calculate the "a" signal.

$$Tout - Thouse = a \tag{5}$$

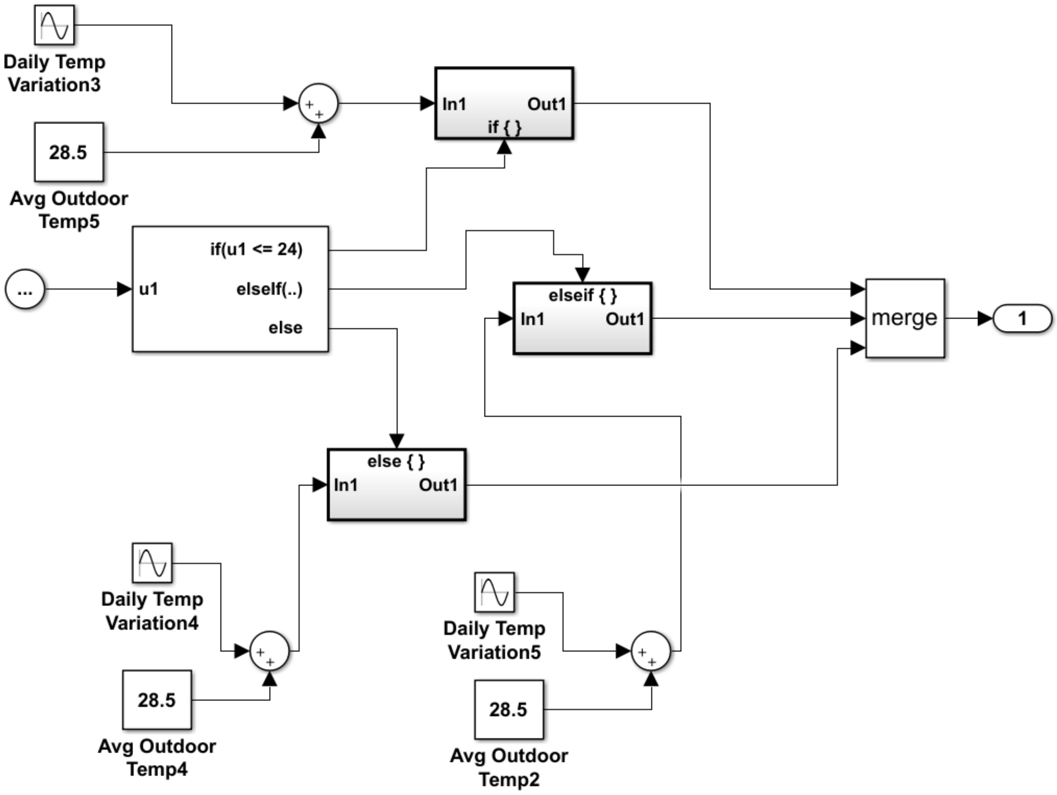


Fig. 7 *Surrounding temperature subsystem*

Subsequently, the signal of "a" which represents the temperature difference will be regulated with thermal equivalent resistance, R_{eq}, to determine cooling losses, "b" signal. Eq. (6) depicts the method for calculating the "b" signal.

$$\frac{a}{\mathrm{R}eq} = b \tag{6}$$

Then, the "b" signal was used to subtract cool losses with the CoolFlow resulting in the determination of the "c" signal which represents differences in cooling rates for the air-conditioning. Eq. (7) outlines the formula used to determine the "c" signal.

$$b - CoolFlow = c \tag{7}$$

Therefore, the "c" signal representing the change of cooling rate will be divided by the product of the house Heat capacity (C) and the total internal air mass (M) to determine the "d" signal. Eq. (8) illustrates the formula for determining the "d" signal.

$$\frac{c}{M \times c} = d \tag{8}$$

Finally, the "d" signal which represents the indoor temperature in °F will be converted using an integral block to convert the measurement into °C.

2.3.2.5 Fuzzy logic controller subsystem

This subsystem diagram illustrates the simulation of the fuzzy logic component implemented in the air conditioning system. It serves as the primary case study for this research project.

Fig. 8 illustrates the construction of the fuzzy logic controller that regulates the expansion valve of the air conditioning system. The controller receives two inputs that are the temperature error (Terr) and the temperature variation error or error adjustment (ΔTerr). The output of the controller is the gas flow. Firstly, the surrounding temperature will result in a sinusoidal wave-shaped variation of the indoor temperature (Tindoor) within the house. This fuzzy logic controller examines the temperature variation resulting from the first subtraction junction where it is subtracted from the set point of 20°C. The temperature error is then analyzed by the thermostat and memory. The thermostat activates the blower. Then, the memory used to store the new temperature error and release the previous temperature error. At the second subtraction junction, the temperature error (Terr) was subtracted from the previous temperature error. This subtraction generates the two input waves (Terrpre) for the fuzzy logic controller.

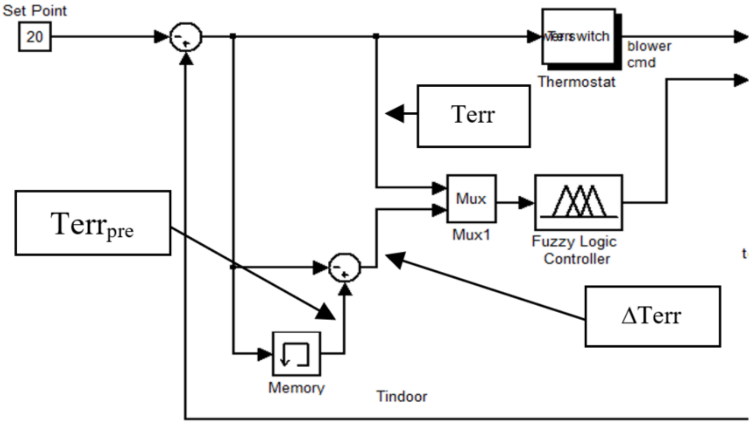


Fig. 8 *Fuzzy logic subsystem*

Eq. (9) and Eq. (10) are used to calculate the temperature error (Terr) and the error of temperature variation or adjustment of error (ΔTerr).

$$Terr = (Tsetpoint) - (Troom) \tag{9}$$

$$\Delta Terr = Terr(Old) - Terr(New) \tag{10}$$

Fig. 9 depicts the waveform for Mux1 comprising the temperature variation error (ΔTerr) and the temperature error (Terr). The red wave indicates the temperature variation error (ΔTerr), while the blue wave represents the temperature error (Terr). The previous cooling house design only accounted for the temperature error (Terr), but the simulation now incorporates the memory component to generate the temperature variation error (ΔTerr). This memory model operates to retain the recent measurement and release the previous measurement. The recent measurement is represented as the new temperature error and the previous measurement is represented as the old temperature by referring to Eq. (9) and Eq. (10).

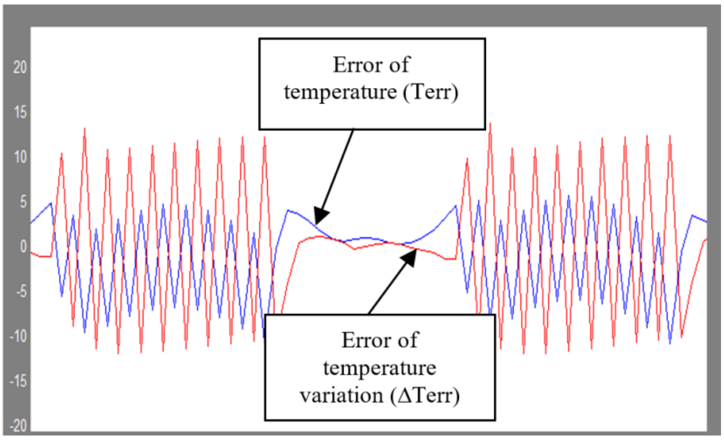


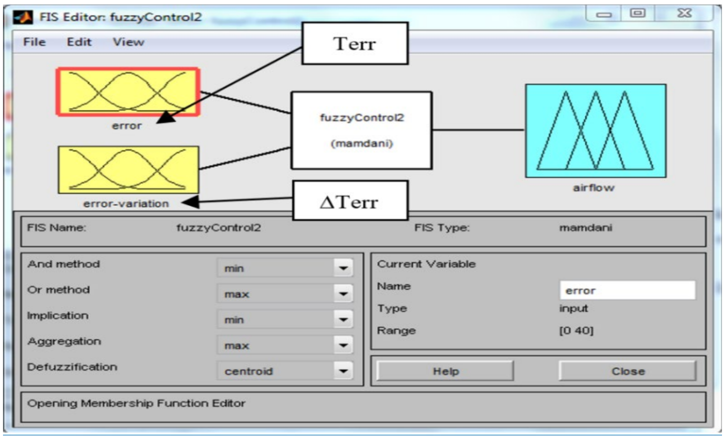
Fig. 9 *Output wave from Mux1*

The purpose of introducing this formulation and circuit to the simulation is to create two inputs that can be processed by the fuzzy logic controller. The wave shape between the temperature variation error (ΔTerr) and the temperature error (Terr) appears to reflect each other since the wave that needs to be analysed by the fuzzy logic controller must synchronize with the membership function rules as depicted in Table 1.

Fig. 10 display the fuzzy logic controller configuration consisting of two inputs of Terr and ΔTerr. Fig. 11 and Fig. 12 demonstrate the membership function inputs of Terr and ΔTerr that each comprising nine membership functions which are low-low (LL), low-medium (LM), low-high (LH), medium-low (ML), medium-medium (MM), medium-high (MH), high-low (HL), high-medium (HM), and high-high (HH). The Mamdani block present in the fuzzy logic controller can be seen in Table 1 and is used to establish the membership function in Fig. 11 and Fig. 12.

Table 1 *Membership function rules*

ΔTerr\Terr	LL	LM	LH	ML	MM	MH	HL	HM	HH
LL	V1	V1	V2	V2	V3	V3	V4	V4	V5
LM	V1	V2	V2	V3	V3	V4	V4	V5	V6
LH	V2	V2	V3	V3	V4	V4	V5	V6	V6
ML	V2	V3	V3	V4	V4	V5	V6	V6	V7
MM	V3	V3	V4	V4	V5	V6	V6	V7	V7
MH	V3	V4	V4	V5	V6	V6	V7	V7	V8
HL	V4	V4	V5	V6	V6	V7	V7	V8	V8
HM	V4	V5	V6	V6	V7	V7	V8	V8	V9
HH	V5	V6	V6	V7	V7	V8	V8	V9	V9



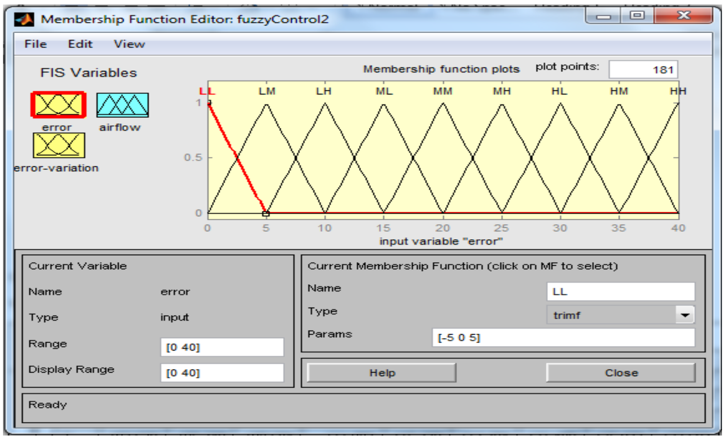
FIS Name: fuzzyControl2
FIS Type: mamdani

And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid

Current Variable
Name: error
Type: input
Range: [0 40]

Opening Membership Function Editor

Fig. 10 *Configuration of fuzzy logic*



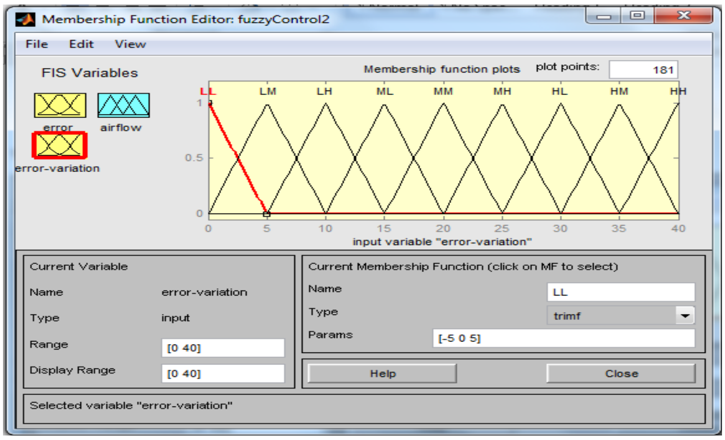
plot points: 181

Current Variable
Name: error
Type: input
Range: [0 40]
Display Range: [0 40]

Current Membership Function (click on MF to select)
Name: LL
Type: trimf
Params: [-5 0 5]

Ready

Fig. 11 *Membership function of Terr*



Membership Function Editor: fuzzyControl2

FIS Variables

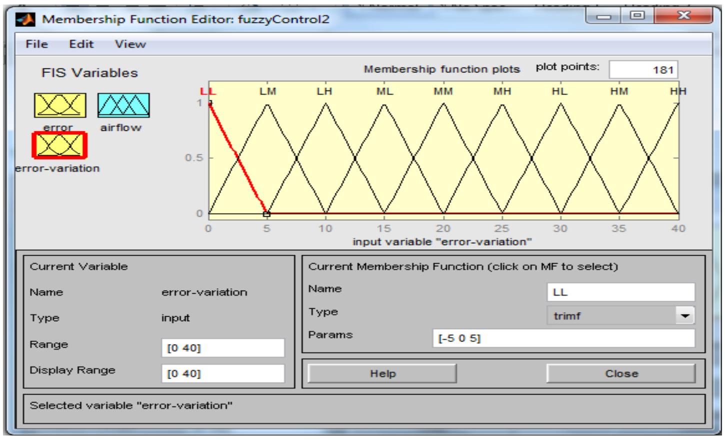
Current Variable
Name error-variation
Type input
Range [0 40]
Display Range [0 40]

Current Membership Function (click on MF to select)
Name LL
Type trimf
Params [-5 0 5]

Selected variable "error-variation"

Fig. 12 *Membership function of ΔTerr*

Fig. 13 illustrates the 9 membership functions of the output airflow namely Valve1 (V1), Valve2 (V2), Valve3 (V3), Valve4 (V4), Valve5 (V5), Valve6 (V6), Valve7 (V7), Valve8 (V8), and Valve9 (V9). This airflow block controls the expansion valve that releases the gas. Fig. 14 display the surface view of input of Terr and ΔTerr, versus output. The x-axis represents Terr, the y-axis represents ΔTerr, and the z-axis represents air flow from the expansion valve. The input range of Terr and ΔTerr as well as the output range of air flow are the same which is 0°C to 40°C. This range is in compliance with the indoor temperature range produced by the surrounding temperature subsystem in Fig. 7.



Membership Function Editor: fuzzyControl2

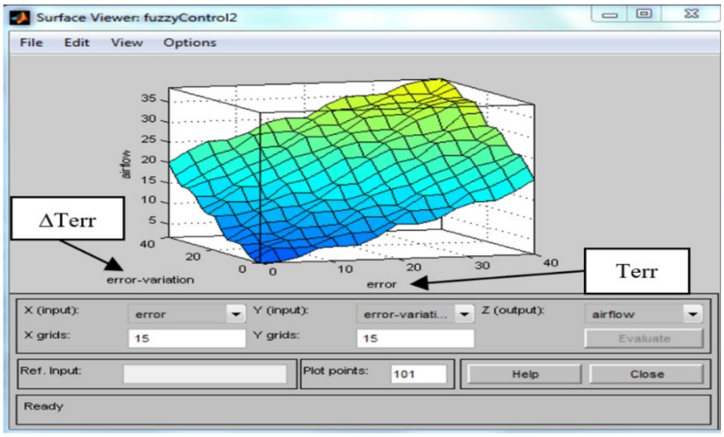
FIS Variables

Current Variable
Name error-variation
Type input
Range [0 40]
Display Range [0 40]

Current Membership Function (click on MF to select)
Name LL
Type trimf
Params [-5 0 5]

Selected variable "error-variation"

Fig. 13 *Membership function of airflow output*



Surface Viewer: fuzzyControl2

X (input): error
Y (input): error-variati...
Z (output): airflow
X grids: 15
Y grids: 15
Ref. Input:
Plot points: 101

Ready

Fig. 14 *The surface view of Terr and ΔTerr*

2.4 Procedure of HVAC Controlled by Fuzzy Logic

The aim of this project is to establish a stable cost-effective HVAC system for a cooling house model. The steps are discussed as follows:

(i) Create the basic cooling model of a house without fuzzy logic controller in Fig. 15 by setting all the parameters needed by the system which is the dimension and material properties (i.e. wall thickness, air density and air flow rate).
(ii) The system was tested and monitored with varying thermostat settings to obtain output in terms of cost.
(iii) The new cooling system for the house which includes a fuzzy logic controller was compared with a system that only uses a thermostat setting. The results of the comparison were analyzed.

The thermostat settings of non-fuzzy logic and fuzzy logic controllers will be recorded by the system. This research aims to compare the performance of the cooling setups in HVAC for both approaches. The procedure aimed to establish cost reductions for both types of cooling setups based on specific house parameters as outlined in step 1.

The project involves modelling a cooling house using Simulink software. Firstly, the initial parameters must be defined including house length, house width, house height, air capacity, thermal resistance, total internal air mass, air flow rate, and initial indoor temperature. These parameters determine the equivalent thermal resistance in Eq. (1) to Eq. (3). The process continues by regulating the air-conditioning subsystem. Fig. 6 shows the regulation of cool air flow into the house via the air-conditioning subsystem. Fig. 7 illustrates the control of surrounding temperature subsystem by Eq. (4). In Fig. 4, the house subsystem employs Eq. (5) to Eq. (8) to measure the oudoor temperature as well as the cooling losses, cooling capacity, indoor temperature, and cooling cost based on the initial parameter used in the cooling process. Fig. 8 shows the fuzzy logic controller subsystem utilizing Eq. (9) and Eq. (10) to generate a membership function rule as illustrated in Table 1. Fig. 10 to Fig. 14 depict the configuration of the fuzzy logic controller subsystem. Finally, the output temperature and cooling cost of HVAC system will be recorded for further analysis.

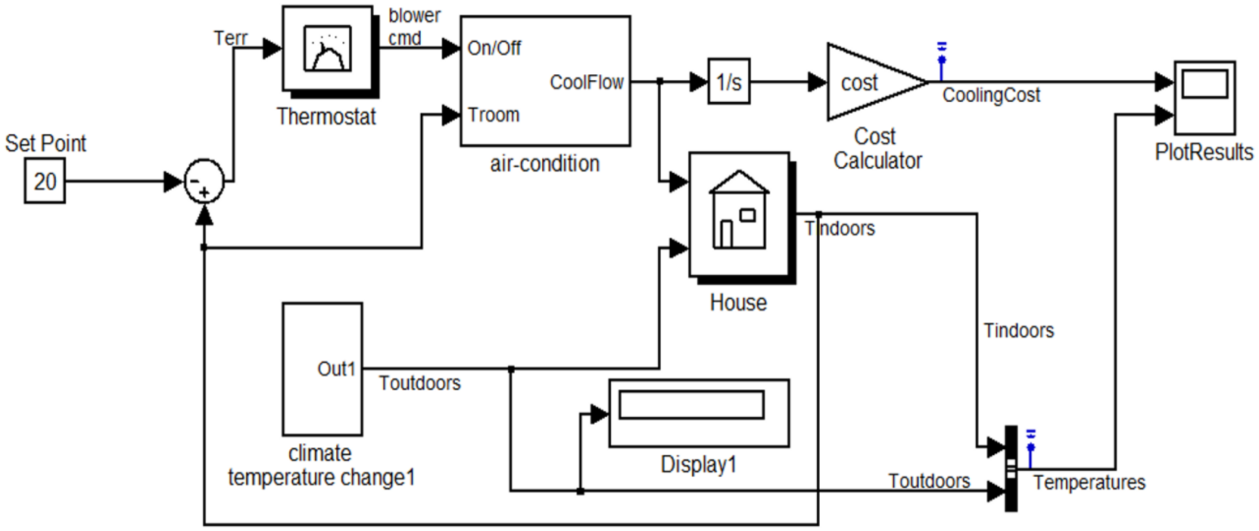


Fig. 15 *Basic model of HVAC without fuzzy logic controller*

3. Results and Discussion

The system shown in Fig. 15 is tested with the thermostat setting given in Fig. 5 where the upper boundary ranges from 0.5^{0}C to 5^{0}C and the lower boundary ranges from -0.5^{0}C to -5^{0}C with both boundaries increasing in steps of 0.5^{0}C and -0.5^{0}C, respectively.

Table 2 present the samples of cooling costs without the inclusion of the fuzzy logic controller. The results are based on varying thermostat settings, with the program running for a total of 72 hours. The highest recorded output cost is RM144.611, with an upper boundary of 0.5^{0}C and a lower boundary of -5^{0}C. Conversely, the lowest cooling cost is RM75.383, with an upper boundary of 5^{0}C and a lower boundary of -0.5^{0}C. This demonstrates that the lowest values of the upper and lower boundaries result in the highest cooling costs. On the other hand, the highest values of the upper and lower boundaries result in the lowest cooling costs.

Table 3 display the samples of output cooling costs of HVAC equipped with the fuzzy logic controller based on various thermostat settings. Based on the observations, altering the lower boundary does not affect the output cooling cost of air conditioning system with the present of fuzzy logic controller. Meanwhile, modifying the upper boundary does impact the output cooling cost of the system. The table demonstrates the uniformity of the output, which may be compared to that of the non-fuzzy logic controller. The comparison between the outcomes presented in Table 2 and Table 3 indicates that the utilization of the fuzzy logic controller in conjunction with the thermostat setting results in a decrease in cooling expenses in the output. The fuzzy logic controller in this circuit able to accurately forecast the optimal cost-effective cooling configuration based on all thermostat settings of a particular house.

Table 2 *Cooling cost (RM) with different thermostat settings without fuzzy logic controller based on 72 hours of operation*

Thermostat setting		Lower boundary/ switch off point									
		-0.5	-1	-1.5	-2	-2.5	-3	-3.5	-4	-4.5	-5
Upper boundary/switch on point	0.5	113.973	117.101	120.466	123.681	126.826	130.089	133.326	136.679	140.457	144.611
	1	110.275	113.493	116.634	120.069	123.281	126.624	130.204	133.215	136.369	140.575
	1.5	106.775	109.785	112.847	116.062	119.136	122.779	126.028	129.542	132.765	136.244
	2	102.620	105.749	108.584	111.983	115.339	117.794	121.480	125.073	127.503	131.971
	2.5	98.694	101.219	104.481	107.062	110.549	113.332	116.149	120172	123.715	126.449
	3	94.312	97.293	99.340	102.855	106.049	107.978	111.206	113.800	118.419	121.666
	3.5	90.076	92.939	94.929	97.370	100.655	103.233	106.247	108.547	110.681	115.508
	4	84.729	87.583	90.249	92.628	94.596	97.980	99.771	103.773	107.712	110.281
	4.5	79.766	81.687	85.473	86.714	89.421	91.709	94.969	98.089	101.148	103.880
	5	75.383	78.642	80.337	82.533	84.077	86.622	90.395	92.678	94.876	97.098

Table 3 *Cooling cost (RM) with different thermostat setting with fuzzy logic controller*

Thermostat setting		Lower boundary/ switch off point									
		-0.5	-1	-1.5	-2	-2.5	-3	-3.5	-4	-4.5	-5
Upper boundary/switch on point	0.5	103.517	103.517	103.517	103.517	103.517	103.517	103.517	103.517	103.517	103.517
	1	103.517	103.517	103.517	103.517	103.517	103.517	103.517	103.517	103.517	103.517
	1.5	98.983	98.983	98.983	98.983	98.983	98.983	98.983	98.983	98.983	98.983
	2	82.802	82.802	82.802	82.802	82.802	82.802	82.802	82.802	82.802	82.802
	2.5	94.184	94.184	94.184	94.184	94.184	94.184	94.184	94.184	94.184	94.184
	3	74.698	74.698	74.698	74.698	74.698	74.698	74.698	74.698	74.698	74.698
	3.5	84.678	84.678	84.678	84.678	84.678	84.678	84.678	84.678	84.678	84.678
	4	77.307	77.307	77.307	77.307	77.307	77.307	77.307	77.307	77.307	77.307
	4.5	65.976	65.976	65.976	65.976	65.976	65.976	65.976	65.976	65.976	65.976
	5	63.613	63.613	63.613	63.613	63.613	63.613	63.613	63.613	63.613	63.613

Table 4 shows the cooling costs for both the system with and without fuzzy logic controller. The highest and lowest cooling cost achieved by the fuzzy logic controller were during 72 and 24 operation hours with savings of 28.41% and 17.51%, respectively. The moderate saving among the three different operation hours was 48 hours with a saving of 15.61%. This result shows that the use of a fuzzy logic controller will significantly lower cooling costs particularly during a 72 hour operation. The reduction in cooling costs is attributed by the contributions of the fuzzy logic controller which regulates the flow of gas at the expansion valve.

Fig. 16 illustrates the variation of outdoor temperature and house temperature under the presence of a fuzzy logic controller.

Table 4 *Comparison between non-fuzzy controller and fuzzy controller in-terms of cost*

Hours of operation (hrs)	Sample cost (Without fuzzy logic controller) RM	Sample cost (fuzzy logic controller) RM	Saving (%)
72	144.6109	103.5175	28.41
48	75.3832	63.6139	15.61
24	98.6937	80.9456	17.51

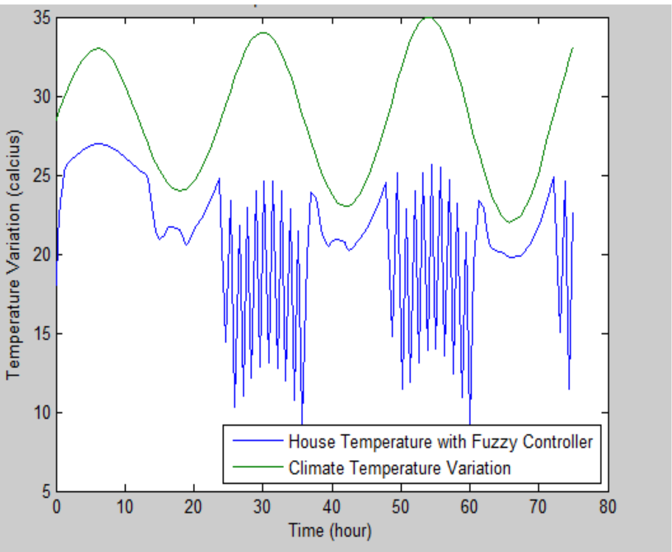


Fig. 16 *Variation of outdoor temperature and house temperature controlled by fuzzy logic*

4. Conclusions

The implementation of fuzzy logic controller indicates a reduction in costs for all operating hours of the HVAC system particularly during 72 hours of operation. In detail, the fuzzy logic controller demonstrates a cost reduction for all HVAC operations of 24, 48, and 72 hours which contributes to 17.51%, 15.61%, and 28.41% savings, respectively. The expansion valve is controlled by the fuzzy logic controller which will sustain the energy conservation of the HVAC system. This method will achieve optimal cooling cost for the HVAC system. The analysis also has shown that adjusting the lower limit of the thermostat has no impact on cooling costs as the fuzzy logic controller maintains optimal cooling. The average output temperature of the HVAC system is 22.63°C considered an optimal temperature. This implies that utilising the fuzzy logic to regulate the refrigerant expansion valve will sustain cost-effective and optimal cooling in HVAC system.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Hasbi Azmi, Muhammad Murtadha Othman, Mohammad Syamir Rodzi;* ***data collection:*** *Muhammad Hasbi Azmi, Muhammad Murtadha Othman, Mohammad Syamir Rodzi;* ***analysis and interpretation of results:*** *Muhammad Hasbi Azmi, Muhammad Murtadha Othman, Mohammad Syamir Rodzi;* ***draft manuscript preparation:*** *Muhammad Murtadha Othman, Ismail Musirin, Masoud Ahmadipour. All authors reviewed the results and approved the final version of the manuscript.*

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