Comparison of Fuzzy and (PID) Techniques in controlling a HVAC System

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Abstract: The performances of four fuzzy Logic Controller (FLC) techniques were investigated and compared with a proportional-integral-derivative (PID) controller, Four user-defined-functions (UDF's) were written and attached to code, ANSYS 12.1 64 bit to simulate the (FLC) actions of four different membership functions (MF's). In all cases, it is required to keep the temperature and humidity in a test room almost at certain setpoints using a simple heating, ventilating, and air-conditioning (HVAC). The results showed that, the performance of (FLC) in most cases was more stable with a very low oscillations around the set points. The temperature response with (FLC) was faster and more stable than that of the (PID) for all the four cases. The humidity response with the (PID) was slightly faster than all (FLC) cases. When defining the fuzzy sets in a power interval, the controller showed an oscillatory temperature response and a slower humidity response than that of all used control techniques.

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1. Introduction

An efficient energy management of building have been the aim of many researchers for many decades. The goal of their research work was always to improve the building energy or cost efficiency and provide better performance. Early techniques were ON/OFF and STEP control which showed effective control performance of local process control loops in HVAC practice. Following these methods, a continuous control method was used in the HVAC, which is (PID) control. (PID) have been more desirable than (PI) or (P) controllers due to the stabilizing effect of a Derivative (D) action, beside its effective manipulation of the fixed disturbance case. That is, in particular, using the proportional participant alone can not control a permanent disturbance process, and unstable response can result from too much high integral gain, so, it was desirable to use (PID) controller system. The latest development of adaptive (PID) and auto-tuning (PID) further ensures the ease and robustness of (PID) applications in industrial process control. Another continuous control technique is the FUZZY, which is more close and similar to human intuition. In much previous research work, this technique appeared to be a simple, robust, and reliable one. Shiuh-Jer Huang and Chen-Chuan Wang [1] proposed an intelligent gain-scheduling fuzzy control strategy to design a temperature controller for an iron closed chamber with heater input only. The concept of gain scheduling is employed to adjust the mapping ranges of fuzzy membership functions, MF's during the control process for improving the control performance. His experimental results showed that the steady-state errors of the step disturbance responses are always less than 0.28C without overshoot by using this control scheme.

Kanagaraj et. al. [2], reduced the outputs steady-state error and dynamic performance in some types of control applications by applying the (PID) type fuzzy control logic, which consists of standard fuzzy controller with three inputs. The inputs are the error, change in error, and sum of error. A. Pacheco -Vega, et. al. [3], have developed a fuzzy-rule-based controller to perform on-line temperature control of a concentric-tube heat exchanger facility. The rules for the controller were derived from dynamical values of the mass flow rates and fluid temperatures in a heat exchanger. The fuzzy controller was embedded in a closed-loop, single-input single-output system to control the outlet temperature of the cold fluid. The information about the system was collected in run time and used to build the corresponding control scheme. Ye Xu and Guohe Huang [4], developed an inexact fuzzy-chance-constrained air quality management model (IFAMM) for regional air quality management to help decision-makers generate cost-effective air quality management patterns. M. Agarwal[5], suggested a procedure that can be used to get a suitable washing time for different cloths. The process is based entirely on the principle of taking non-precise inputs from the sensors, subjecting them to fuzzy arithmetic and obtaining a crisp value of the washing time. his method could be used in practice to further automate the washing machines, and was applied in giants like LG and Samsung. Y. Yamakawa and T. Yamazaki[6], simplified the complex thermal system of a building to be a space enclosed by an envelope exposed to certain outdoor conditions. Then they suggested a mathematical formulas to estimate the initial control signal and to offset thermal loads before they affect the control output. and to confirm the effectiveness of the manual reset compensation. In the present work, it is intended to compare the control efficiency of both (PID) and, Fuzzy Logic Controller,(FLC) techniques, when controlling a HVAC system. The (PID) technique had been investigated in a previous work [7], and the case which showed the best performance will be compared with four cases of (FLC). Each one of the four cases has four inputs, two outputs, and a different MF's. The four inputs are error and rate of error for temperature and humidity.

2. Estimating the initial Loads

It is required to estimate the thermal loads as well as moisture that are produced in a real room. The room is exposed to air and sun light, and occupied by one person who uses some electric appliance. The following equations were used, [9] and [10].

2.1 Exposed Wall Load Calculations, table 1,

$Q_h = A * U_O *(CLTD)$ (1)

Where, the cooling load temperature factor, (CLTD) and its correction are shown for each wall in table 1.

Table 1. cooling load temperature factor and its correction

WALL	CLTD (^oK)	Corrected(CLTD)(^oK)
N	8.0	2.2
E	9.7	3.8
S	9.1	3.3
W	10.8	5

2.2 infiltration and Ventilation:-

in a real room, it is required to estimate the excess sensible and latent loads due to infiltration and Ventilation, so, the following equations may be used, [10],

$q_{vi,s} = cs(q_{vi} + (1 - \varepsilon s)q_{bal,\,hr} + q_{bal,\,oth})\Delta t$ (2)

$q_{vi,\,l} = cl(q_{vi} + q_{bal,oth})\Delta w$ (no hrv/erv) (3)

$q_{vi,t} = ct(q_{vi} + (1 - \varepsilon t)\, q_{bal,hr} + q_{bal,oth})\Delta h$ (4)

$q_{vi,l} = q_{vi,t} - q_{vi,s}$ (5)

Where, hrv or erv are heat or energy recovery ventilators.

2.3 sensible and Latent internal Loads: -

in a real room, it is required to estimate the sensible and latent internal gains, so, the following equations may be used, [10],

$q_{ig,s} = 136 + 2.2A_{cf} + 22Noc$ (6)

$q_{ig,l} = 20 + 0.22A_{cf} + 12Noc$ (7)

Table 2. Indicates a summary of all load components. After estimating the thermal and moisture loads in a real occupied room it is possible to produce the same conditions in the test room.

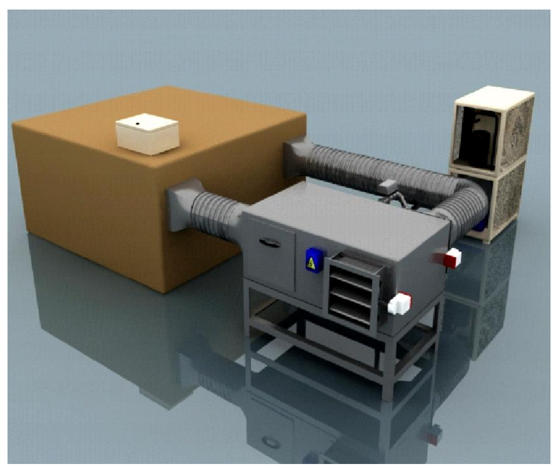
Table 2. summary of the load components.

Load	Description
2769.0 Btu/hr 811.6 Watts	Wall Load
89.7 Btu/hr 26.3 Watts	Conduction through Door
183.6 Btu/hr 53.8 Watts	Sensible
140 Btu/hr 41 Watts	Latent
14674.4 Btu/hr 4300 Watts	Equipment Load
465 Btu/hr 136.3 Watts	Lighting
852.52 Btu/hr 249.3 Watts	infiltration – Ventilation
19173.9 Btu/hr 6510 Watts	total load
0.00004 kg/s	Moisture rate /occupant

3. Test Room

The case was simulated by a test room, which is described in [1], and is shown in fig. 1,

Figure. 1. The test room



4. Fuzzy Rules

The ranges of temperature and humidity variations and their corresponding ranges of required cooling energy and fresh air were determined according to the previous experimental work (1), and by performing some preliminary numerical runs, as a kind of trial and errors, because the equations (8) and (9) are approximate formulas, and the values resulting from them need to be corrected. These runs were performed while the disturbance macros were disabled. The temperature varied within the range from 290 to 306 K, its rate varied from -0.5 to +0.5 K/s, whereas, humidity varied from 0.006 to 0.012 kg/kg air, its rate varied from -0.0004 to +0.0004 kg/kg air/s. The required "initial" cooling rate was found to be 7.1 Watts, and the initial fresh air rate is 0.11 kg/s. Thus, in each one of the simulated methods, we have six ranges; temperature error, its rate of change, required removed heat, humidity error, its rate of change, and required fresh air. Each one of the ranges of input errors and their rates was divided into two equal divisions; one is for negative variation and the other is for positive variation. Whereas, each one of the ranges of cooling and fresh air was divided into two divisions, each one is equal to the initial value. Each one of these quantities appears in fig. 2 as percentage of "the division". For the five teeth curves, (FTC) , each division is divided into two subdivisions, and for both the nine teeth curves, (NTC) and the nine sine curves, (NSC), each division is divided into four subdivisions, but for the nine power divisions, (NPD), each division is divided into four "unequal" subdivisions, which are increasing in a power function. Each subdivision represents the support of a corresponding fuzzy set, and is referred to as a "level". The rules were assembled according to the results of the preliminary runs and the practice experiences. Some of them were eliminated, because their conditions are unlikely to occur. The rules are:-

IF ((T is within level '1') and ($\overset{*}{T}$ is within level '1')) THEN cooling is set within level '1', the above rule ,although seems unrealistic, but, is necessary, because the first control scan starts after the highest disturbance is achieved.

IF ((T is within level '1') and ($\overset{*}{T}$ is within level '6')) THEN cooling is set within level '9'.

IF ((T is within level '1') and ($\overset{*}{T}$ is within level '7')) THEN cooling is set within level '2'.

IF ((T is within level '1') and ($\overset{*}{T}$ is within level '8')) THEN cooling is set within level '3'.

IF ((T is within level '2') and ($\overset{*}{T}$ is within level '7')) THEN cooling is set within level '3'.

IF ((T is within level '2') and ($\overset{*}{T}$ is within level '8')) THEN cooling is set within level '3'.

IF ((T is within level '3') and ($\overset{*}{T}$ is within level '4')) THEN cooling is set within level '3'.

IF ((T is within level '3') and ($\overset{*}{T}$ is within level '5')) THEN cooling is set within level '4'.

IF ((T is within level '3') and ($\overset{*}{T}$ is within level '6')) THEN cooling is set within level '4'.

IF ((T is within level '4') and ($\overset{*}{T}$ is within level '3')) THEN cooling is set within level '3'.

IF ((T is within level '4') and ($\overset{*}{T}$ is within level '4')) THEN cooling is set within level '4'.

IF ((T is within level '4') and ($\overset{*}{T}$ is within level '5')) THEN cooling is set within level '4'.

IF ((T is within level '4') and ($\overset{*}{T}$ is within level '6')) THEN cooling is set within level '5'.

IF ((T is within level '5') and ($\overset{*}{T}$ is within level '4')) THEN cooling is set within level '4'.

IF ((T is within level '5') and ($\overset{*}{T}$ is within level '5')) THEN cooling is set within level '5'.

IF ((T is within level '5') and ($\overset{*}{T}$ is within level '6')) THEN cooling is set within level '6'.

IF ((W is within level '1') and ($\overset{*}{W}$ is within level '1')) THEN Fresh air is set within level '1', and again, this rule , is necessary for numerical consideration.

IF ((W is within level '1') and ($\overset{*}{W}$ is within level '6')) THEN fresh air is set within level '9'.

IF ((W is within level '1') and ($\overset{*}{W}$ is within level '7')) THEN fresh air is set within level '2'.

IF ((W is within level '1') and ($\overset{*}{W}$ is within level '8')) THEN Fresh air is set within level '3'.

IF ((W is within level '2') and ($\overset{*}{W}$ is within level '7')) THEN fresh air is set within level '3'.

IF ((W is within level '2') and ($\overset{*}{W}$ is within level '8')) THEN fresh air is set within level '3'.

IF ((W is within level '3') and ($\overset{*}{W}$ is within level '4')) THEN fresh air is set within level '3'.

IF ((W is within level '3') and ($\overset{*}{W}$ is within level '5')) THEN fresh air is set within level '4'.

IF ((W is within level '3') and ($\overset{*}{W}$ is within level '6')) THEN fresh air is set within level '4'.

IF ((W is within level '4') and ($\overset{*}{W}$ is within level '3')) THEN fresh air is set within level '3'.

IF ((W is within level '4') and ($\overset{*}{W}$ is within level '4')) THEN fresh air is set within level '4'.

IF ((W is within level '4') and ($\overset{*}{W}$ is within level '5')) THEN fresh air is set within level '4'.

IF ((W is within level '4') and ($\overset{*}{W}$ is within level '6')) THEN fresh air is set within level '5'.

IF ((W is within level '5') and ($\overset{*}{W}$ is within level

'4')) THEN fresh air is set within level '4'.

IF ((W is within level '5') and ($\overset{*}{W}$ is within level '5')) THEN fresh air is set within level '5'.

IF ((W is within level '5') and ($\overset{*}{W}$ is within level '6')) THEN fresh air is set within level '6'.

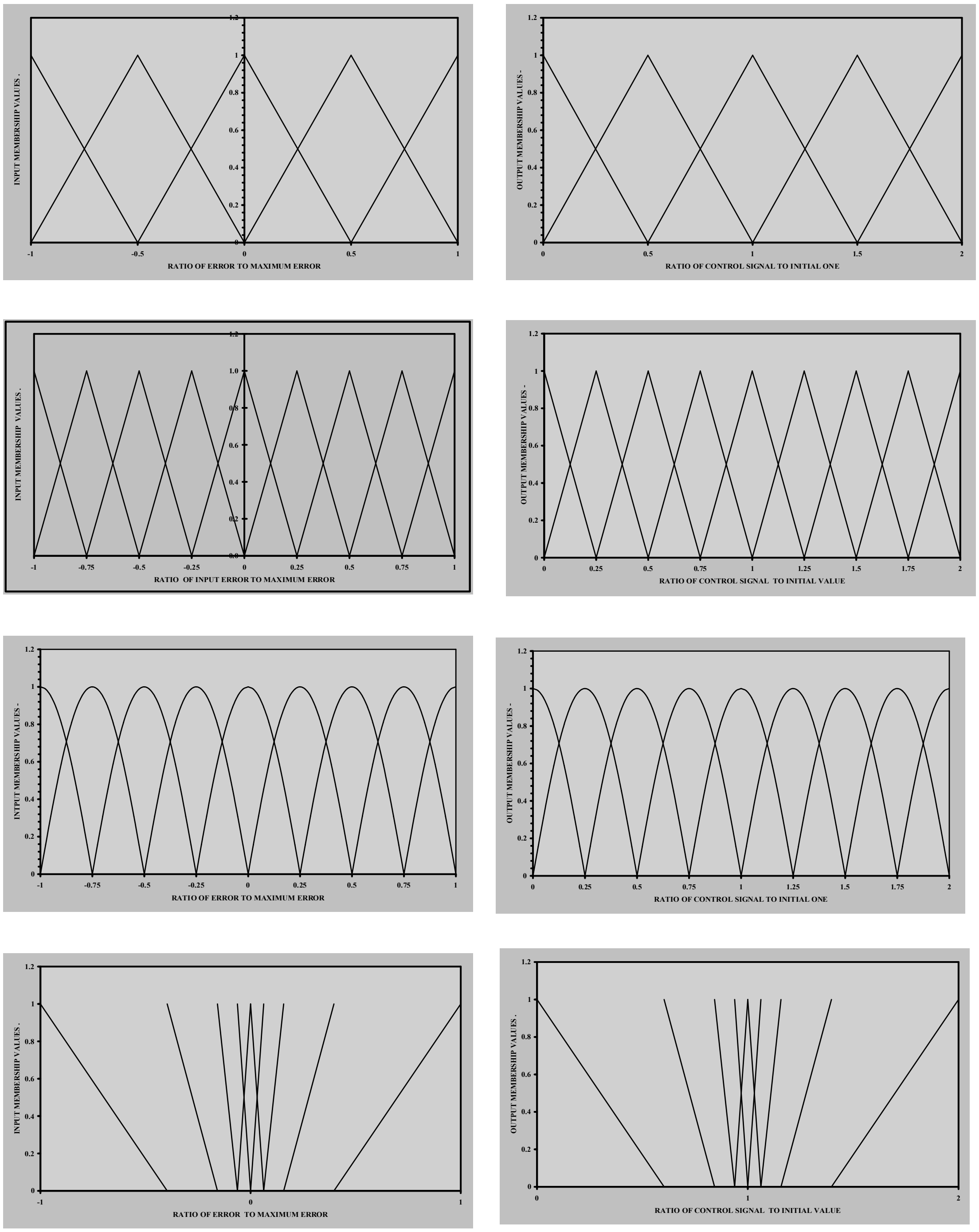


Figure. 2. input and output membership functions ; top- to bottom: (FTC) , (NTC) , (NSC) , and (NPD) .

5. Simulating the Control Mechanism

5.1 formulations

In the present work, it is required to simulate a test room which receives a mixture of fresh air and exhaust air. Before this mixture enters the room, it is cooled by chilled water. The rates of fresh air, exhaust air, and chilled water are determined according to the control signals. These signals are supplied from the control unit to manage two stepper motors and a solenoid valve. Each stepper motor controls the blades of a damper, whereas, the solenoid valve controls the rate of chilled water. In a previous work [1], this control system was controlled by a programmable logic controller, (PLC), with two (PID) modules. The rate of chilling water is used to offset the thermal loads, whereas, the rate of fresh dry air is used to control the humidity. The disturbances in temperature was produced by admitting hot air through a separate opening and the humidity disturbances was produced by a steam humidifier. The test room details and all thermal and moisture sources were simulated using the code "gambit 2.3.16". Four user defined functions, (UDF) where written and tested to simulate the four MF's. These (UDF,s) join a commercial code, Ansys 12.1 64 bit, which solves the momentum, scalar quantities, and species conservation equations. The first essential requirement is to determine the "initial" rates of fresh air and removed heat by chilled water , since they correspond to the set points of both temperature and humidity in case of no disturbances. Equations [8] and [9] are mass and enthalpy balances to estimate theoretical values for them,

$$m_f = \beta\ (1.0+w_f)^*\ w_{load} / (w_{re}- w_f) \qquad (8)$$

$$q_{ch} = m_{fd} *(h_f - h_{re}) + q_l + m_m *h_{dif} \qquad (9)$$

$$h_{re}=cp*T_{re} + w_{re}*(2500.9+1.82*T_{re}) \qquad (11)$$

$$h_{dif}= \gamma\ (cp\ + w_{in}*1.82) \qquad (12)$$

$$h_f=cp*T_f + w_f*(2500.9+1.82*T_f) \qquad (13)$$

where, h_f, h_{re}, and h_d are calculated using the formula suggested in [12]. The temperature T_f, in the experimental work of [1], varied during one hour from about 29.9 ^{o}C to 32.3 ^{o}C, and this variation with time could be fitted to the following polynomial, which was found to give accurate prediction for fresh air temperature,

$$t_f = 29.9466 + 0.000702863*t + 5.50668e\text{-}007*t^2 - 2.85235e\text{-}010\ \ t^3 + 4.4714e\text{-}014*t^4 \qquad (14)$$

The parameters β and γ are correction factors to compensate for the differences between the values estimated by the theoretical formulas [8] and [9], and the actual values. To estimate the values of β and γ, the disturbance macros were first disabled, and a number of preliminary runs were performed with different trial values until the results, which are more close to the setpoints of temperature and humidity are achieved. Another preliminary runs were performed, while the disturbance macros were enabled, to estimate crude values for the ranges of the expected temperature and humidity errors, which are necessary for the fuzzification processes . Both values of q_{ch} and m_f could be transformed into the corresponding initial control signals which will be sent to the dampers and the chilled water valve. To simulate the inlet mixture temperature and humidity, during the run, after calculating the initial required fresh air and cooling water, the following balance equations were used to estimate inlet conditions,

$$w_i = (m_{fd}*w_f + m_{red}*w_r)/(m_{fd}+m_{red}) \qquad (15)$$

$$t_i = (m_{fd}*h_f+m_{red}*h_r - (m_{fd}+m_{red})*w_i*2500.9- q_{ch}) / ((mfd+m_{red})*(cp+wi*1.82)) \qquad (16)$$

During the preliminary runs, it was observed that, a fast steady state condition occurred after about 300 seconds, due to the higher inlet mass flow rate, with respect to the relatively small test room volume, which resulted in a faster thermal and moisture mixing. The disturbance macros were designed to start after achieving the steady state, until the set point values are almost achieved.

Note : in every control scan, previous fresh air rate was stored to be used in calculating the percentage of its variation between two successive control scans. This percentage is used to add additional cooling rate, (positive or negative) to the current cooling rate, due to the change in inlet fresh air as follows,

$$Q_{ch} = q_{ch,\ current}\ \ x\ (1.0 + \psi\ \ x\ (m_{f,\ current} - m_{f,\ previous})/ m_{f,\ previous}\ ) \qquad (17)$$

From the preliminary runs, the additional cooling rate factor, ψ, due to the change in fresh air level, was found to be around 0.2.

5.2 Description of a (UDF) for the (NSC)

The (UDF), which was written to simulate the (NSC), as example, consists of the following sections :-

- A section for the reservation of a) variables and arrays which will store all values appearing in equations 8 through 17. b) another variables and arrays to store the controlled variables, their rates, and their membership degrees to each one of the nine sine curve fuzzy sets. c) counters and flags necessary for the program logic.
- A section for the definition of the nine sine curve membership functions.
- A macro that calculates all initial conditions (at time step 1), such as inlet and outdoor conditions, and all parameters necessary to implement equations (8), through (14).
- A macro that implement equations (8), through (14), to calculate the errors, (after averaging over all domain nodes) and their time rates, each time step.
- A section for adjusting the inlet fresh air temperature with time, (each five minutes), according to equation (14), and all values depending on it such as; fresh and return air enthalpy and their

rates.
- Four macros which calculate the current control signals for both temperature and humidity control according to the thirty two rules, using the Center of Gravity, (COG) method.
- Two macros to calculate profiles for the inlet temperature and humidity, (after mixing).
- A section for the Print out of a) the calculated average errors each time step (for the purpose of monitoring), b) the calculated errors against time at end of program execution, (for additional postprocessing).

6. Model Verification

A case was experimentally studied with the following conditions:
- Set points for temperature and humidity are: 298 K and 0.009 kg/kg air, respectively.
- (NTC) membership function is chosen,
- Total air mass flow rate is 0.33 kg/s
- the chilled water valve and the fresh air damper blades were adjusted to give rates of cooling water and fresh air of 7.13066 W and 0.18117 kg/s, respectively, which was estimated from the preliminary runs. The heaters and lamb were operated first for five minutes, then, the blower, humidifier, and, the chiller unit were operated. Both dry and wet bulb temperatures were continuously observed until, the steady state was achieved. From both temperatures, the absolute and relative humidity were obtained according to [12]. The temperature disturbance is initiated by opening the window for 30 seconds, and during the same interval, the humidity disturbance was operated by raising the humidifier steam rate from 0.00004 to 0.00006 kg /s. To check the controller performance in worst conditions, it was turned on after the end of disturbance interval, with the calculated initial control signals. The dry and wet bulb temperatures, which are used in calculating the humidity, have been recorded until, the set points are approached. The results were compared with those produced by the numerical simulation. Fig. 3 illustrates an accepted agreement between the experimental run and its simulation.

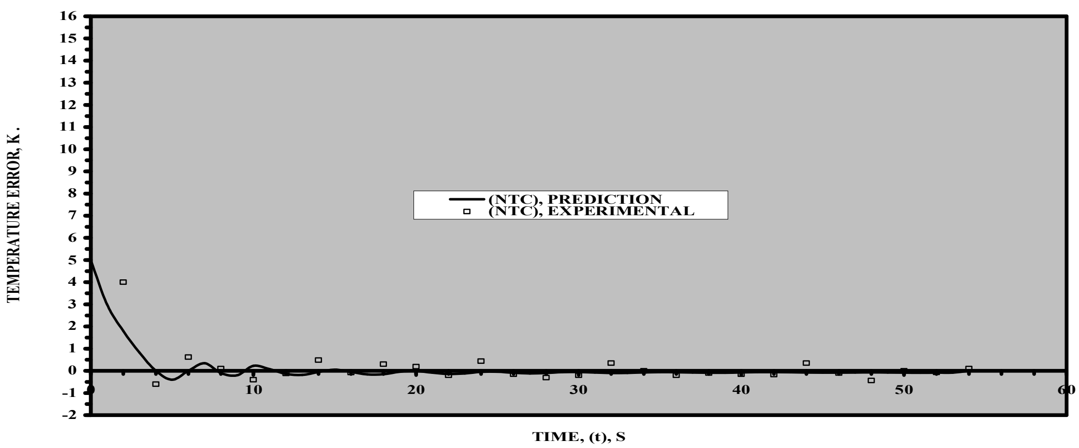


Figure. 3. Response of (NTC) control, experimental and prediction.

7. Results and Discussion

The present work includes an investigation of four fuzzy control arrangements, and a comparison between their performances and that of (PID) controller, which was operated with its optimum tuning parameters, as described in [1]. Fig. 4 illustrates a comparison of the temperature predictions for all the fuzzy methods and the (PID). In all cases, the speed of response was higher than that in the real size room, because the used inlet air and cooling rates were large with respect to the smaller size test room. It is observed that, all the fuzzy methods have a faster temperature response than that of the (PID) one, and the fuzzy method with the (NTC) and (NSC) showed the fastest responses with little damped oscillations toward the set point, and the (NPD) showed a continuous oscillatory behavior. This may be interpreted as follows, in (PID), every control scan accumulates a change in control signal which produce a slower creeping toward the set point. With fuzzy technique, a different output set is chosen every control scan according to the sensed error set, and consequently, this allows a faster change toward the set point. In NPD case, the sudden enlargement of the fuzzy 'supports' leads to a sudden change in the calculated control signal, which may results in the oscillatory behavior. The (FTC) showed slower movement toward the set point with, almost, no observed oscillations. For the humidity responses, fig. 5, (PID) method indicated a faster creeping toward the set point than all other methods, and the (FTC) and

(NPD) had slowest movements toward the set points. The diffusion of moisture to the relatively dry fresh air is slow, which give a chance to the integral participant of (PID) to accumulate more control signal divisions during successive control scans. Even after the error responds to the control signal and starts to decrease, the integral participant keeps accumulating smaller divisions to the previous control signal in a few fractions of second, which increase the control efficiency in decreasing the humidity error. With fuzzy techniques, when there is a slow response, the controller will keep the output signal within the same output 'set'. So, with slow moisture diffusion, the effect of accumulating control signal divisions in (PID) exceeds that of fuzzy, which immediately chooses the output signal 'set'.

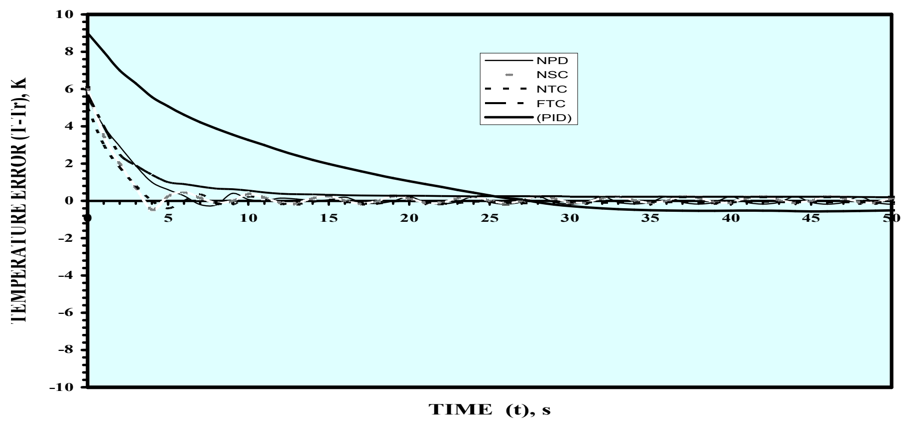


Figure 4. Temperature response with each of the control methods; (NPD) , (NSC) , (NTC) , (FTC) , and (PID)

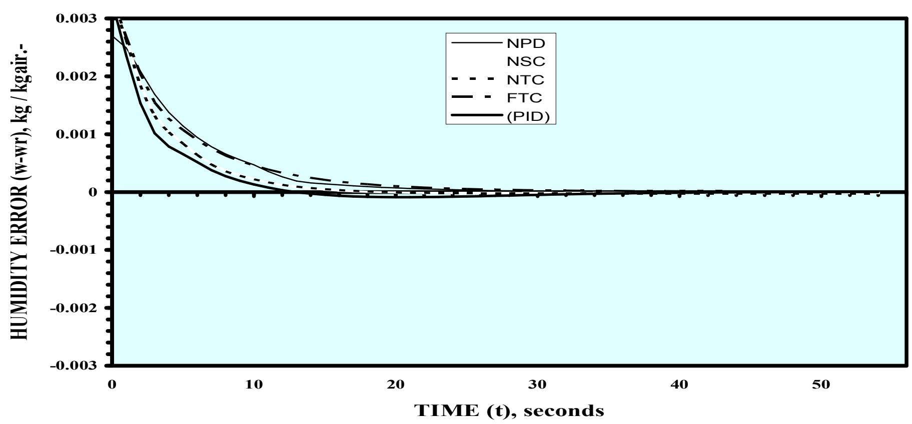


Figure 5. Humidity response with each of the control methods; (NPD) , (NSC) , (NTC) , (FTC) , and (PID).

8. Conclusion

The temperature and humidity control for a simple HVAC system was investigated using four fuzzy control arrangements and a (PID) controller. The comparison of the temperature responses indicated that, all the fuzzy methods have a faster temperature response than that of the (PID) one, and the fastest of all were (NTC) and (NSC), and the (NPD) showed a slower oscillatory behavior. The (PID) method indicated a little increase in the humidity response than all other methods, and the (FTC) and (NPD) had the slowest response of all. (FLC) is a simple reliable control technique, which is an effective method in controlling temperature in simple HVAC systems, but, the (PID) technique is slightly more efficient in controlling humidity.

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