SIMULATION OF SELF-TUNING PID-TYPE FUZZY ADAPTIVE CONTROL OF A HVAC SYSTEM

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Key words: *Self-Tuning PID-Type Fuzzy Adaptive Controller, Fuzzy PD-Type Controller, Classical PID Controller, HVAC.*

ABSTRACT

The modeling, numerical simulation and control of a HVAC (heating, ventilating and air-conditioning) system having two different zones with variable flow-rate were performed by considering the ambient temperature in this study. The sub-models of the system were obtained by deriving to heat transfer equations of heat loss of two zones by conduction and convection, cooling unit and fan. All models of the variable flow-rate HVAC system were generated by using MATLAB/SIMULINK and PID parameters were obtained by using Fuzzy sets. For comfortable of human being, the temperatures of the two different zones were decreased 5°C from the ambient temperature. The successful results were obtained by applying self-tuning PID-type Fuzzy adaptive controller if comparing with the fuzzy PD-type and the classical PID controller. The obtained results were presented in graphical form.

I. INTRODUCTION

In this study, it was shown that the usage of modelling and simulation methods for analysing, testing and developing of HVAC systems decreased the design cost as well as the design process. Furthermore, the obtaining better performances of the simulated systems became easier. S. Soygüder and H.Alli studied the classical PID control of HVAC system having two zones with different properties [1]. K_p, K_i and K_d parameters of PID were obstained to minimize the system error in their study, however, the steady-state error was not totally eliminated.
In addition to PID control of HVAC systems, Fuzzy Logic Control (FLC) of HVAC systems was studied by many authers [2-3]. The obtained results were compared with those of PID control and these studies indicated that FLC had better results. FLC is extensively used in processes where systems dynamics is either very complex or exhibit a highlynonlinear characters. The first FLC algorithm implemented by Mamdani [4] was designed to synthesize the linguistic control protocol of an experienced operator. Althoug this type of FLC application was successful compared to classical controllers, the design procedure is dependent on the experience and knowledge of the operator and it is limited by the elucidation of the heuristic rules of control. To avoid this major disavantage of depending on the control experience of the operator, MacVicar-Whelan [5] firstly proposed some general rules fort he structure of fuzzy controllers. These fuzzy ruless devised by MacVicar-Whelan approach to a deterministic (PI) or (PD) controller in the limit as quantization levels of control and measurement variables become infinitely fine [6]. It was shown that the beter results for the same system was obtained by using FLC with respect to PID control. However, control rule sets for FLC are quite diffucult to redesign.To eliminate to this negative condition, self-tuning FLC can be designed and applied to HVAC systems. The obtained results showed that the self-tuning advanced FLC reached the optimal solution according to the described performance criteria [7]. In addition to PID control and FLC of HVAC systems, the studies on combining PID and FLC for HVAC systems were performed [8-9]. Based on these studies, the modelling of HVAC systems with variable flow-rate has been established by using MATLAB/SIMULINK and K_p, K_i and K_d parameters of PID have been determined by using self-tuning PID type fuzzy adaptive controller. The performance of the proposed control algorithm has been compared with that of of the classical PID and fuzzy-PD type controllers. As a result of simulations, it has been show that the performance of the proposed controller is better among the others. The instantaneous time-dependent solution of the system has been obtained for each zone and model by considering the input and output valves of each device and the desired comfortable conditions. The temperatures of two different zones for each time-step and the required damper gap rates for supplying the desired comfortable conditions have been found in the result of the numerical

simulations. The obtained results have been presented in graphical form.

II. HVAC SYSTEM HAVING TWO DIFFERENT ZONES

The cooling process has been performed for two zones having different properties as shown in Figure 1. The volume of each zone is $0.5m^3$. All surfaces of Zone-1 were covered by the isolation materials (strafor) however those of Zone-2 were not. The purpose of this type of design is to see and determine clearly the steady-state differences to obtain the reference temperatures for two zones having different properties. The cooled air transfer has been realized from the main channel having the supply fun to the regions of Zone-1 and Zone-2. The temperature controls of the two zones were realized by the proposed controllers by regulating the damper gap rates. The air supply fan first absorbs 5^oC air from the evaporator, then sends to the zones as shown in Figure 1.

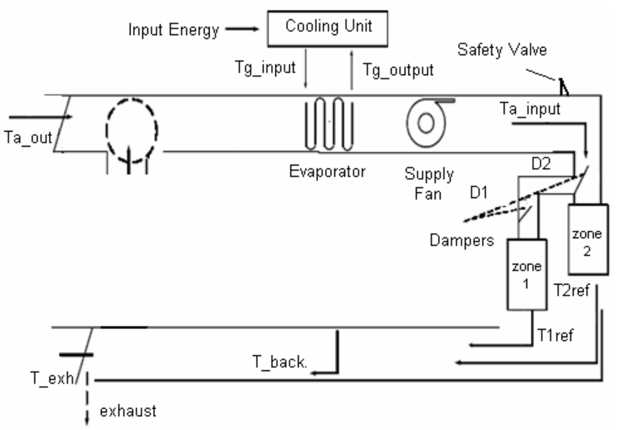


Figure 1: The schematic view of the HVAC system having two zones

The mass flow-rate ($\dot{m}_{ca}$) absorbed from the cooling unit does not change because the supply fun has constant the number of revolution. However, the mass flow-rate of the air entering to the zones changes depending on the temperatures of the zones. The continously variations of the input mass flow-rate ($\dot{m}_{z1a,in}$) Zone-1 and ($\dot{m}_{z2a,in}$) Zone-2 are realized by regulating the gap rates of dampers into the entrances of zone-channells, depending on the control output signals.The continuity equation of the controlled system can be formed as:

$$\dot{m}_{ca} = \dot{m}_{z1a,in} + \dot{m}_{z2a,in} + \dot{m}_{sva,out} \qquad (1)$$

The mass flow-rate $\dot{m}_{sva,out}$ in Equation-1 belongs to the safety valve discharging the excessive air coming from the zones.The variable-input mass flow-rates of the zones are provided by the damper motors. The damper gap rates are changed between 0^o to 90^o, depending on the zone temperatures. In the beginning of the control process, the damper gap rate for each zone is 90^o as a maximum value. The damper gap rates decreasingly become 0^o depending on the control parameters when the zone temperatures reaches the desired temperatures. The designers should take account that the flow-speed of the air in the zones does not exceed to 0.15 m/s because of the comfortable conditions. This condition has been realized by using the exhaust valve mounted to the exist of the zones. The exhaust mass-flowrate ($\dot{m}_{exha,out}$) has been controlled by manuel in this study.

III. THE MODEL OF THE HVAC SYSTEM

The transient and steady-state behaviors, controllability, control performances, design of energy-effective systems and analysis of HVAC systems can be performed by obtaining system models and using simulation tools. Furthermore, the effects of controllers on the controlled system can be examined. In addition to that, system modelling leads to minimize the design process of mechanical systems [10]. Figure 1. shows the schematic diagram of the modelled system in this study. The main elements of the system: The cooling zone-areas, Evaporator, Cooling unit, Fan, Dampers motors,Channels, Thermocouples. We define the symbol lists indicated in Table 1. Obtaining of the mathematical model of the cooled zone by considering all paremeters is quite difficult. Fort this reason, we consider the following assumptions:

1) The effect of the instantaneous variations of air speed in the zones on the pressure is neglected.
2) There is no air leakage except the exhaust valves of the zones.
3) The air flow in the zones is homogeneous.

There is no change in the flow-rates of the zones since the input flow-rate equals to the output flow-rate. That's why we can write the continuity equation as:

$$\dot{m}_{za,in} = \dot{m}_{exha,out} = \dot{m}_{za} \qquad (2)$$

According to thermodynamic first law, the internal energy equation can be stated as follows:

$$Q\text{–}W+\sum \dot{m}_{za,in}\,.\,h_{in} - \sum \dot{m}_{exha,out}\,.h_{out} = \frac{du}{dt} \qquad (3)$$

where u represents time-dependet variation of heat. Furthermore, Equation 3 can be re-written as the following form, assuming that there is no work in the system.

$$Q + \dot{m}_{za}.\,(h_{in}\text{-}h_{out}) = \frac{du}{dt} = \frac{m_{za}.C_v.(T_{n-1}-T_n)}{dt} \qquad (4)$$

$$h_{in} - h_{out} = C_p\,.\,(T_{ca,in}\text{-}T_n) \qquad (5)$$

If Equation 4. is rearranged, we get:

$$Q+\dot{m}_{za}\,.\,C_p\,.\,(T_{ca,in}\text{-}T_n)=\frac{m_{za}.C_v.(T_{n-1}-T_n)}{dt} \qquad (6)$$

$$Q + \dot{m}_{za} \cdot C_p \cdot (T_{ca,in}-T_n) = m_{za} \cdot C_v \cdot \frac{dT}{dt} \qquad (7)$$

where T represents the instantaneous temperature variation. The heat transfer from the outside to the system can be stated as:

$$Q = \frac{T_{out} - T_n}{R} \qquad (8)$$

or:

$$Q = \frac{T_{out} - T_n}{\frac{1}{h_{out}.A} + \frac{L_1}{k_1.A} + \frac{L_2}{k_2.A} + \frac{1}{h_{in}.A}} \qquad (9)$$

If Equation 9 is substituted in Equation 8, we get:

$$\frac{dT}{dt} = \frac{Q + \dot{m}_{za}.C_p(T_{ca,in} - T_n)}{m_{za}.C_v} \qquad (10)$$

IV. SELF-TUNİNG PID-TYPE FUZZY ADAPTİVE CONTROL

The self-tuning PID-type fuzzy controller is an auto-adaptive controller that is designed by using an incremental fuzzy logic controller in place of the proportional term in the conventional PID controller to tune the parameters of PID controller on line by fuzzy control rules. The controller uses the error and the rate of change of error as its inputs and can meet desire of self-tuning parameters based on time-varying e and $\dot{e}$.

$$u(k) = K_P\, e(k) + K_i \sum^{k} e(i) + K_d\,[e(k)-e(k-1)] \qquad (11)$$

Where K_p is controller gain; $K_d = K_p T / T_i$;
$K_d = K_P T_D / T$; T is sample-time ; T_i is integral time parameter ; T_D is derivative time parameter [11]. Because the proposed fuzzy self-tuning PID controller aims to improve the control performance yielded by a PID controller, it keeps the simple structure of the PID controller and it is not necessary to modify any hardware parts of the original control system for implementation. Fuzzy self-tuning of PID parameters is finding out the fuzzy relation between PID three parameters and e, $\dot{e}$. It examines incessantly e and $\dot{e}$ in work then tunes three parameters with fuzzy control rules on line so that controlled objects achieve better dynamic steady performance. The self-tuning adaptive control method has been applied to HVAC systems as the other systems. There are many studies on determining the paremeters of controllers and finding new values of controller paremeters according to changing situations. The optimum control method has been used to find the required-control paremeter values that the heater provides the designed temperatures and humidities in HVAC systems [12]. First of all, the error and the variation of error depending on the measured T1 and T2 temperatures, which are belong to two zones having different properties are taken as the inputs of Fuzzy-PD type controllers. Mamdani's fuzzy inference method is used the system with two inputs and one output. The output (the control variable), which is the mass flow-rate of the cooled air entered the zones, is determined depending on the defined the rule base of e and ($\dot{e}$) ,with the aim of minimizing the error. Once we define the rule base indicated in Table 2, we now need to determine the membership functions for e, ($\dot{e}$) and u shown in Figure 2.

Table 2 The Rule Base for Fuzzy PD-Type Control

	$\dot{e}$					
	u	**NB**	**NS**	**Z**	**PS**	**PB**
e	**NB**	NB	NB	NS	NS	Z
	NS	NB	NS	NS	Z	PS
	Z	NS	NS	Z	PS	PS
	PS	NS	Z	PS	PS	PB
	PB	Z	PS	PS	PB	PB

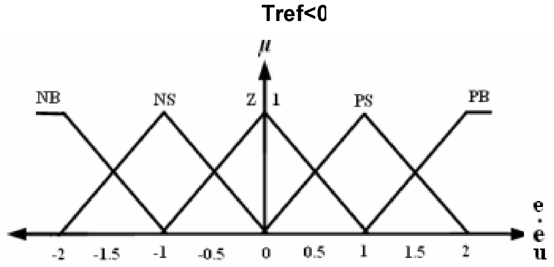


Figure 2. The membership functions for the input e , $\dot{e}$ and the output u

A membership function is a curve that defines how each point in the input space is mapped to a membership value (on degree of membership) between 0 and 1. In this case, the triangular membership functions are used for all variables and {-2, -1.5, -1, -0.5, 0, 0.5, 1, 1.5, 2} physical domain is selected for all variables based on trial and error method. The fuzzy variables are defined for the rule base as, e, ($\dot{e}$), u = {the error, the variation of error, the control variable {NB (Negative Big), NS (Negative Small), Z (Zero), PS (Positive Small), PB (Positive Big)}, [-2, 2], μ}

The fuzzy rule base is constructed by using several if-then statements and premise and consequent of each statement are fuzzy propositions. Table 2. indicates that 25 rules defines the rule base for the fuzzy-PD type controller. For the aim of the comparesion of the control performance, the control of the same HVAC system has been realized by aplied the self-tuning PID-type fuzzy adaptive controller. We combine the classical PID and FLC theories in this study. The K_p, K_i, K_d values of PID paremeters have adaptively been determined by using the dynamic FLC for each time-step. In this case, FLC has two inputs (e, $\dot{e}$) and three outputs (K_p, K_i, K_d).

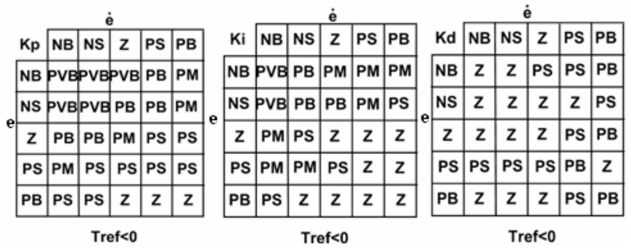
The gauss membership function are used for all variables shown in Figure 5 and 6. The physical domain of the inputs (e, $\dot{e}$) is {-1, -0.8, -0.6, -0.4, -0.2, 0, 0.2, 0.4, 0.6, 0.8, 1} and that of the outputs (K_p, K_i, K_d) is {0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1}, selected again based on trial and error. The fuzzy variables are defined for the rule base as,

e, ($\dot{e}$) = {the error, the variation of error, {NB (Negative Big), NS (Negative Small), Z (Zero), PS (Positive Small), PB (Positive Big)}, [-1, 1], µ}

K_p, K_d, K_i = {the control paremeters, {Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big), PVB (Positive Very Big), [0, 1], µ}

Table 3. indicate the rule bases for K_p, K_d and K_i, respectively.

Table 3. The rule base for K_p ,K_i , K_d



Kp	NB	NS	Z	PS	PB
NB	PVB	PVB	PVB	PB	PM
NS	PVB	PVB	PB	PB	PM
Z	PB	PB	PM	PS	PS
PS	PM	PS	PS	PS	PS
PB	PS	PS	Z	Z	Z

Tref<0

Ki	NB	NS	Z	PS	PB
NB	PVB	PB	PM	PM	PM
NS	PVB	PB	PB	PM	PS
Z	PM	PS	Z	Z	Z
PS	PM	PM	PS	Z	Z
PB	PS	Z	Z	Z	Z

Tref<0

Kd	NB	NS	Z	PS	PB
NB	Z	Z	PS	PS	PB
NS	Z	Z	Z	Z	PS
Z	Z	Z	Z	PS	PB
PS	PS	PS	PS	PB	Z
PB	Z	Z	Z	PS	PB

Tref<0

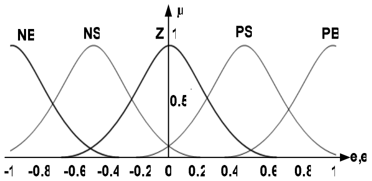


Figure 5. The membership functions for the inputs e ve $\dot{e}$

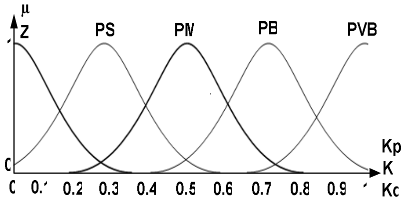


Figure 6. The membership functions for the outputs K_p-K_d-K_i

V. THE NUMERİCAL SİMULATİON OF THE HVAC SYSTEM

The model, control and numerical simulation of the HVAC system having two zones with different properties have been realized by using MATLAB/SIMULINK package programme. The instantaneous time-depented solution of the system has been obtained for each zone and model by considering the input and output values of each device and the desired comfortable conditions. The temperatures of two considered zones for each time-step and the required damper gap rates for suppliying the desired comfortable conditions have been found in the result of the numerical simulations. The obtained results have been presented in graphical form. Figure 8. show the block diagrams of the considered HVAC system controlled by the self-tuning PID-type fuzzy adaptive controller. In these figures, T1ref and T2ref are the desired reference temperatures of Zone-1 and Zone-2, respectively. FLC provides the control signals (u1,u2) to minimize error depending on e and ($\dot{e}$). The obtained control signals change the damper gap rates and the air mass flow-rates entered the zones to reach the desired reference temperatures. Figure 9. show the flow-chart of the considered HVAC system controlled by the self-tuning PID-type Fuzzy Adaptive controller. For numerical simulation, the ambience temperature has been taken as 31.3 ^{o}C. The desired reference temperature has been selected as 26.5 ^{o}C for Zone-1. Figure 10. shows the temperature control of Zone-1 when the classical PID, Fuzzy-PD type and the self-tuning PID-type fuzzy adaptive controller are applied. The performance of the self-tuning PID-type fuzzy adaptive controller is best among the others in terms of both the steady-state error and the the settling time. There is no steady-state error and the system reaches the desired reference temperature with the minimizim settling time. Although the fuzzy-PD type controller has no the steady-state error, it has longer settling time. The worst performance belongs to the classical PID controller. Figure 11. shows the variation of the damper gap rates for Zone-1 for the considered three controllers. The on and off positions of damper are also shown in this figure. The channell area is 0.02 m^2. The 90^o position of the damper is the full open position and the system has the maximum mass flow-rate. The 0^o position of the damper is the closed position of the damper and the cooled air can not pass through the Zone-1. The desired reference temperature for Zone-2 is 27.5 ^{o}C. Figure 12. shows the temperature variations of Zone-2 when the considered three controllers are applied. The system has been cooled from 31.3 ^{o}C to the desired temperature 27.5 ^{o}C. Again, the self-tuning PID-type fuzzy adaptive controller performs the best without the steady-state error and having the minimum settling time if we compare with the others. Figure 13. indicates the damper gap rate variations for Zone-2. The time histories of the damper positions are clearly seen in this figure. Figure 14. shows k_p-k_i-k_d variation of Zone-1 when the self-tuning PID-type fuzzy adaptive controller. Further, Figure 15. shows k_p-k_i-k_d variation of Zone-2 when the self-tuning PID-type fuzzy adaptive controller.

As a result, the self-tuning PID-type fuzzy adaptive controller is more applicable for HVAC systems among the others.

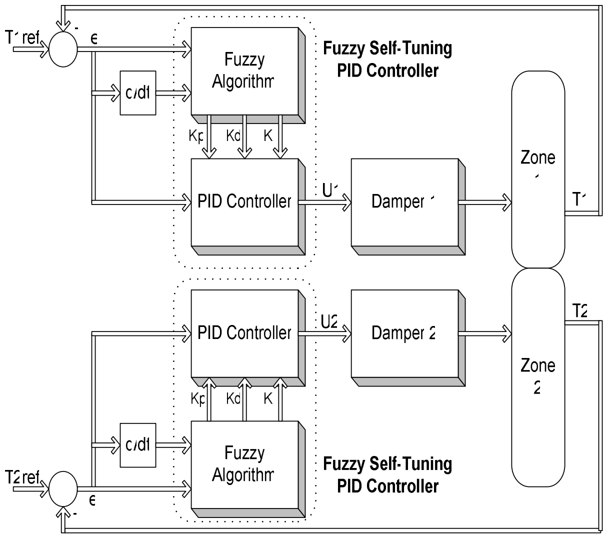


Figure 8. The block diagram of the self-tuning PID-type fuzzy adaptive controller

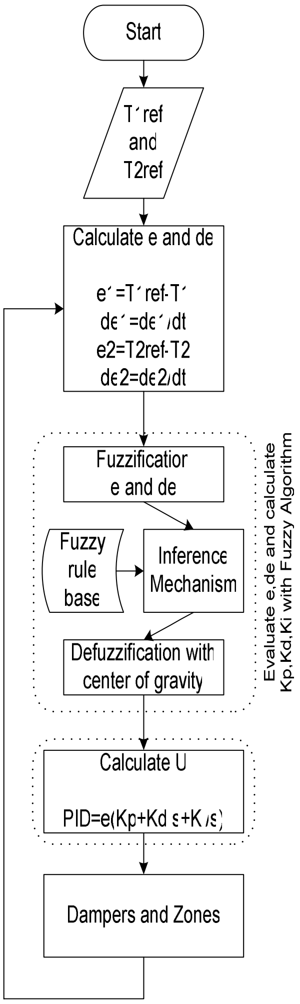


Figure 9. The flow-chart of the self-tuning PID-type fuzzy adaptive controller

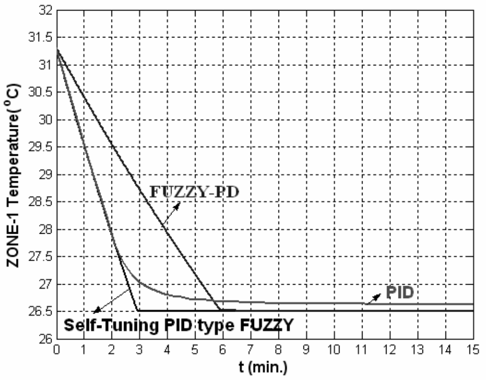


Figure 10. The temperature variation of Zone-1 when the classical PID, fuzzy-PD type and the self-tuning PID-type fuzzy adaptive controller are applied

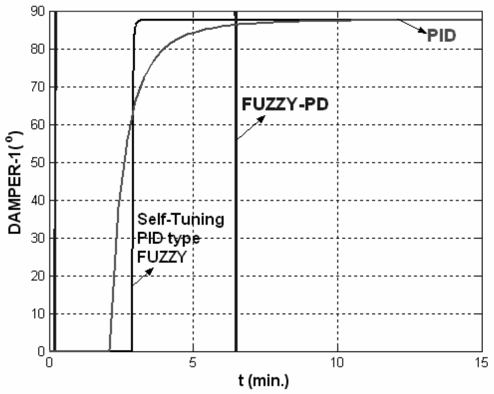


Figure 11. The damper gap rate variation for Zone-1 when the classical PID, fuzzy-PD type and the self-tuning PID-type fuzzy adaptive controller are applied

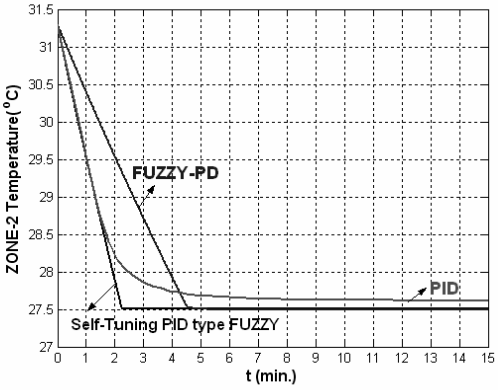


Figure 12. The temperature variation of Zone-2 when the classical PID, fuzzy-PD type and the self-tuning PID-type fuzzy adaptive controller are applied

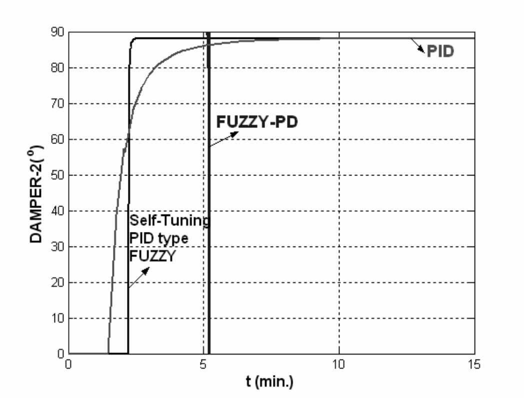


Figure 13. The damper gap rate variation for Zone-2 when the classical PID, fuzzy-PD type and the self-tuning PID-type fuzzy adaptive controller are applied

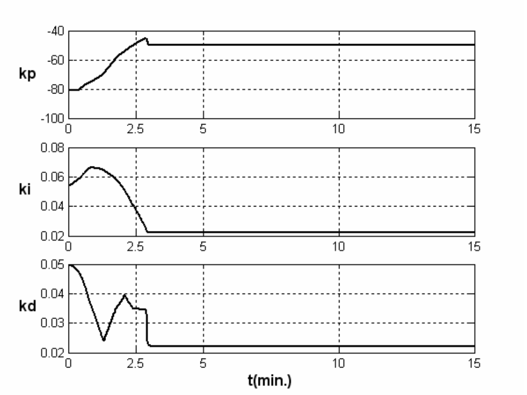


Figure 14. k_p-k_i-k_d variation of Zone-1 when the self-tuning PID-type fuzzy adaptive controller

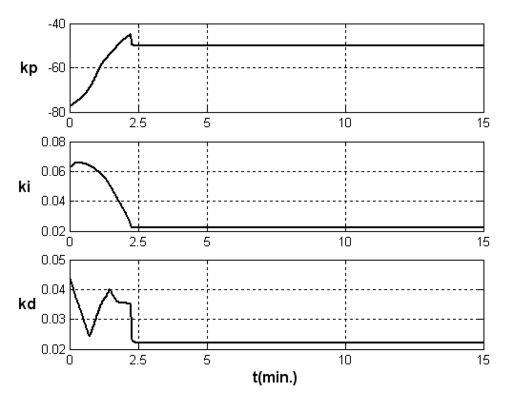


Figure 15. k_p-k_i-k_d variation of Zone2 when the self-tuning PID-type fuzzy adaptive controller

VI. CONCLUSİONS

The numerical simulation of the cooling process from the ambient temperature to the desired reference temperatures of the HVAC system having two zones with different properties has been realized. The instantanous time-dependent solution of the considered HVAC system has been found for each zone and model by considering the input and output values of each device and the desired comfortable conditions. The temperatures of two zones and the required damper gap rates for providing the desired conditions for each time-step have been obtained by using the numerical simulations. The numerical simulation of the system applied the classical PID [7], fuzzy-PD type and the self-tuning PID-type fuzzy adaptive controller has been realized by using MATLAB/SIMULINK package programme. The obtained figures indicate that the performance of the self-tuning PID-type fuzzy adaptive controller is the best among the others, in terms of both the steady-state error and the settling time. The proposed controller leads to the considered HVAC system having the minimum settlings time and without the steady-state errors. The obtained results makes the proposed controller more effective among the others.

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Table 1. Symbol List

A	Area (m^2)
$\dot{m}_{ca}$	The mass flow-rate in fan channell (kg/s)
$\dot{m}_{z1a,in}$	The mass flow-rate entered to Zone-1 (kg/s)
$\dot{m}_{z2a,in}$	The mass flow-rate entered to Zone-2 (kg/s)
$\dot{m}_{sva,out}$	The mass flow-rate exist from safety valve (kg/s)
$\dot{m}_{exha,out}$	The mass flow-rate exist from exhaust (kg/s)
Q	Convection and Transmission Heat (J)
W	Work (J)
$\dot{m}_{z1a,in} = \dot{m}_{za}$	The mass flow-rate entered to Zone-1 (kg/s)
h_{in}	Specific Enthalpy(J/kg)
h_{out}	Specific Enthalpy (J/kg)
U	The internal energy (J)
C_v	Constant Heat (kJ/kgK)
C_p	Constant pressure (kJ/kgK)
T	İnner temperature (^oC)
T_n	İnstant temperature (^oC)
T_{n-1}	Vicious circle temperature (^oC)
$T_{sh,gir}$	Cool air temperature (^oC)
T_{out}	Outside temperature (^oC)
h_{out}	Convection coefficient for outside-surface (J/m^2K)
h_{in}	Convection coefficient for inner-surface (J/m^2K)
k	Transmission coefficient (J/mK)
L_1	Thickness for Zone-1 (m)
L_2	Thickness for Zone-2 (m)