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Fuzzy Approach for Cascade Control of Interconnected System

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Abstract: The methodology proposes fuzzy logic Proportional-Integral-Derivative (fuzzy PID) and fuzzy cascade controller architecture and its performance have been compared with the classical control techniques such as Conventional Feedback Control (CFC) and Conventional Cascade Control (CCC) for continuous stirrer tank heater. Fuzzy logic control technology has been widely used and successfully utilized in numerous industrial applications. The Proposed Control architecture is effective especially when the controlled object operates under uncertainty or in the presence of a disturbance. This design methodology introduces a new controller structure has been achieved by blending classical and fuzzy logic controller in an intelligent way. The configuration of fuzzy PID controller is basically composed of three parallel fuzzy subcontrollers. The additional conventional PID controller placed in parallel with fuzzy subcontrollers are grouped together to form the overall fuzzy PID controller. The fuzzy cascade controller consists of fuzzy PID as primary controller and fuzzy logic Proportional-Integral (fuzzy PI) as secondary controller. The simulated results show that the fuzzy control approach gives improved control performances than the conventional controllers particularly in handling nonlinearities and external disturbances. The performance of various control strategy has been compared in terms of Integral Square Error (ISE).

Key words: Fuzzy PID, fuzzy PI, conventional feedback control, cascade control, fuzzy logic control, classical control

INTRODUCTION

The Continuous Stirrer Tank Heater (CSTH) is widely used in chemical industry as a heat exchanging equipment in which process stream is heated with saturated steam so that its premixed components achieve a uniform composition. Heating systems can be either direct or indirect. In the electrical heating process heat energy is to be transfer in small amount through resistive type electrical coil which carries incomplete mixing of premixed component. Indirect heating systems are most widely used in which heat is received from carrier fluids such as steam, hot oil, hot water or air, molten salt mixtures etc. Indirect heating is preferable when large quantities of heat are to be transported over considerable distances, it can be best done by flowing fluid as a carrier of thermal energy. Temperature control is important because high temperature tends to decompose the product while a low temperature results in incomplete mixing. A hot fluid circulated through a jacket and heat flow between the jacket and vessel increases the energy content of the vessel fluid. Stirrer is used for uniform distribution of temperature in process vessel (Gopal, 1997; Stephanopoulos, 2004). The classical and advance temperature control strategy is tested on simulated CSTH process. The schematic diagram of CSTH as shown in Fig. 1.

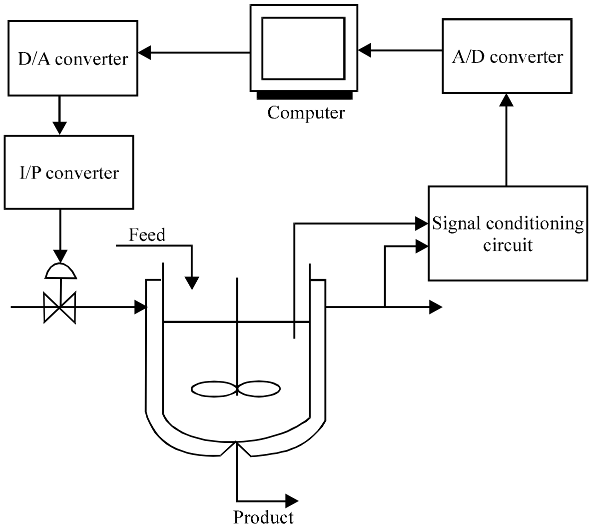

Fig. 1: Schematic diagram of CSTH process

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During the past several years the classical control techniques are widely used in process industries to control various processes. Conventional PID controllers are oftenly used in most of the temperature control loop. PID control is one of the earliest tactics. The conventional PID controllers are widely used in actual industry systems due to their simplicity in arithmetic, ease of using good robustness, high reliability and stabilization. It is also well known that PID controller exhibit poor performance when applied to systems containing unknown nonlinearity such as dead zones, saturations and hysteresis. It is difficult to achieve efficient control of time variable and nonlinear plants with conventional PID controllers. The proper PID control requires that the proportional, integral and derivative settings be tuned accurately which is not so easy task. It is also equally difficult or impossible to implement with Multiple Inputs Multiple Output (MIMO) systems. Also some processes behave in nonlinear, complex ways, so that conventional PID controller cannot adequately control them. Conventional feedback control produces poor response for large load disturbances. To overcome from this disadvantage cascade control configuration is implemented for regulating the temperature in continuous stirrer tank heater (Seborg *et al*., 2004; Wen and Liu, 2004).

Fuzzy logic controller is very suitable for a controlled object with nonlinearity and even with unknown structure because of their knowledge based nonlinear structural characteristics. Recently hybrid fuzzy logic control approach is widely used in process control applications in which classical PID and fuzzy controller have been combined by blending mechanism that depends on a certain function of actuating error. Hybridization of these two controller structures comes to ones mind immediately to exploit the beneficial sides of both categories. An Intelligent switching scheme is induced on the blending mechanism that makes a decision upon the priority of the two controller parts. The control structure of hybrid fuzzy logic is based on mamdani type fuzzy inference technique (Petrov *et al*., 2002; Taneva *et al*., 2004).

The new proposed control architecture mainly consists of two cascaded fuzzy logic controllers such as fuzzy PID and fuzzy PI. Fuzzy PID controller as a primary controller while fuzzy PI controller as a secondary controller in an advanced control techniques. The objective of this research is to compare the results of proposed control architecture with classical control techniques such as conventional feedback control and cascade control configuration.

SYSTEM MODELING AND CONTROL

Process description: In CSTH, the objective is to raise the temperature of inlet stream to desired value. A heat transfer fluid is circulated through a jacket to heat the fluid in the tank. The following assumptions are made for simplified analysis:

- The liquid inflow and outflow rates for the tank are equal so that the liquid level in the tank is manipulated constant during the operation
- The tank is kept at a uniform temperature by perfect mixing with the help of a stirrer. Thus a single temperature is used to describe the thermal state of the entire liquid. The temperature inside the tank equals to temperature of the out flowing liquid
- The heat storage capacity of the tank walls is negligible

Energy balances on the vessel and jacket fluids results in the following equations:

$$\frac{dT}{dt} = \frac{F}{V}(T_i - T) + \frac{UA}{V\rho C_p}(T_j - T) \tag{1}$$

$$\frac{dT_j}{dt} = \frac{F_j}{V_j}(T_{jin} - T_j) - \frac{UA}{V_j\rho_j C_{pj}}(T_j - T) \tag{2}$$

Where:

T and T_j = The output temperature
T_j and T_{jin} = The inlet temperature
C_p and C_{pj} = The heat capacities
ρ and ρ_i = The fluid density
V and V_j = The volumes for tank and jacket, respectively
U = The overall heat transfer coefficient
A = The area of heat transfer (Goel *et al*., 2005; Luyben, 1996)

The energy balance equation describes the behavior of the continuous stirrer tank heater is generally nonlinear while commonly used control strategies are based on linear systems theory. The relationship between the temperature of process fluid in tank and hot fluid in jacket is nonlinear in nature as shown in Fig. 2.

Optimize PID control: Temperature control loops are usually moderately slow because of sensor lags and the process heat transfer lags. The optimize PID control scheme is implemented for nonlinear transfer function model of CSTH.

The nominal parameter values of CSTH process are shown in Table 1 which are required in simulation. The nonlinear transfer function model is derived from Eq. 1 and 2:

$$\frac{V}{F}\frac{dT}{dt} = (T_i - T) + \frac{UA}{F\rho C_p}(T_j - T) \tag{3}$$

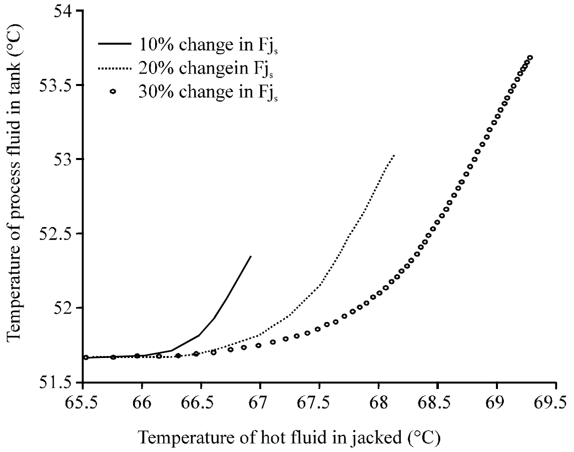

Fig. 2: Nonlinear relationship between temperature of process fluid in tank and jacketed fluid

Table 1: Nominal parameter values of CSTH process model

Parameter	Symbol	Value
Flow rate of process fluid	F	28.32 L min^{-1}
Flow rate of heat transfer fluid	F_j	42.48 L min^{-1}
Volume of process tank	V	283.2 L
Volume of jacket	V_j	70.8 L
Inlet temperature of process fluid	T_i	10°C
Outlet temperature of process fluid	T	51.667°C
Density of process fluid and specific heat of process fluid	$\rho\ C_P$	4111.391 J L^{-1} °C
Density of heat transfer fluid and specific heat of heat transfer oil	$\rho_j\ C_{Pj}$	4111.391 J L^{-1} °C
Inlet temperature of heat transfer fluid	T_{jin}	93.333°C
Outlet temperature of heat transfer fluid	T_j	65.55°C
Overall heat transfer area and heat transfer coefficient	UA	346454.4643 J L^{-1} min

$$\frac{V}{F}\frac{dT}{dt}+\left(1+\frac{UA}{F\rho C_p}\right)T=T_i+\frac{UA}{F\rho C_p}*T_j \tag{4}$$

Taking Laplace transform and rearranging term of Eq. 3 and 4:

$$T_{(s)}=\frac{T_{i(s)}+K_1T_{j(s)}}{(\tau_1 s+K)} \tag{5}$$

Where:

$$\tau_1=\frac{V}{F};K_1=\frac{UA}{F\rho C_P};K=(1+K_1)$$

$$\frac{V_j}{F_j}\frac{dT_j}{dt}=(T_{jin}-T_j)-\frac{UA}{F_j\rho_jC_{pj}}(T_j-T) \tag{6}$$

$$\frac{V_j}{F_j}\frac{dT_j}{dt}+\left(1+\frac{UA}{F_j\rho_jC_{pj}}\right)T_j=T_{jin}+\frac{UA}{F_j\rho_jC_{pj}}*T \tag{7}$$

Taking Laplace transform and rearranging term of Eq. 7:

$$T_{j(s)}=\frac{T_{jin(s)}+K_2T_{(s)}}{(\tau_2 s+\bar{K})} \tag{8}$$

Where:

$$\tau_2=\frac{V_j}{F_j};K_2=\frac{UA}{F_j\rho_jC_{Pj}};\bar{K}=(1+K_2)$$

From Eq. 5 and 8 we can develop closed loop block diagram as shown in Fig. 3. The block diagram reduction technique is used for determining nonlinear transfer function model of CSTH process with disturbance model is given as follows:

$$T_{(s)}=G_{P(s)}T_{jin(s)}+N_{(s)}T_{j(s)} \tag{9}$$

The overall transfer function of CSTH process is represented with their disturbance which is used in simulation for regulating temperature parameter through optimize PID controller method.

Consider the temperature control of CSTH process using optimize PID controller is as shown in Fig. 4 in which optimization method is used for controller setting. The temperature T is controlled output while the inlet temperature T_{in} is the load and flow rate of jacketed fluid F_j is manipulated variable.

The objective is to raise the temperature of the inlet stream to a desired value. A heat transfer fluid is circulated through a jacket to heat the fluid in the tank. The overall response will be rather sluggish and a PI controller will make it even more so. Consequently, for such nonlinear processes optimize PID controller would be the most appropriate because it can allow high gains for faster response without undermining the stability of the system.

The tuning parameters of nonlinear process are determined from optimization method. Modulus Optimum (BO) and Symmetrical Optimum (SO) are two methods for selecting and tuning controllers that are similar in spirit to Haalman's method. The nonlinear transfer function model of CSTH process represent in the form of following equation:

$$G_{P(s)}=\frac{K'_P}{(1+sT_1)(1+sT_2)},\quad T_1>T_2 \tag{10}$$

Where:

K'_p = The process gain
T_1 and T_2 = The time constants of process. The Tuning parameters
K_p = The proportional gain
T_i = The integral time
T_d = The derivative time are determined from symmetrical optimization method which is given as follows:

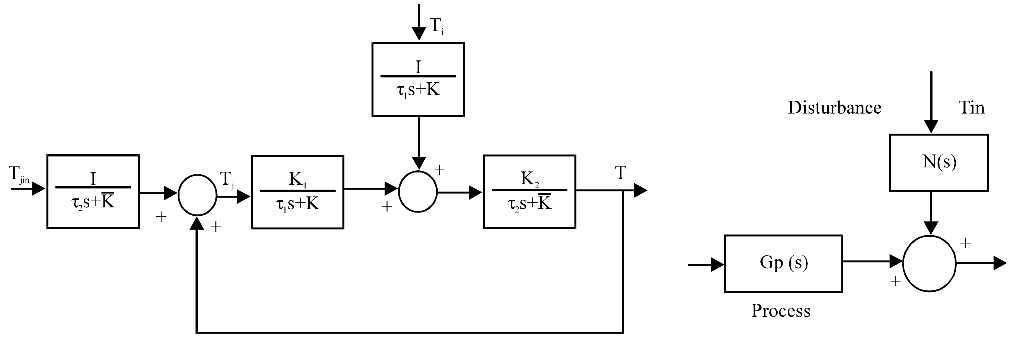

Fig. 3: Closed loop block diagram of CSTH process transfer function model

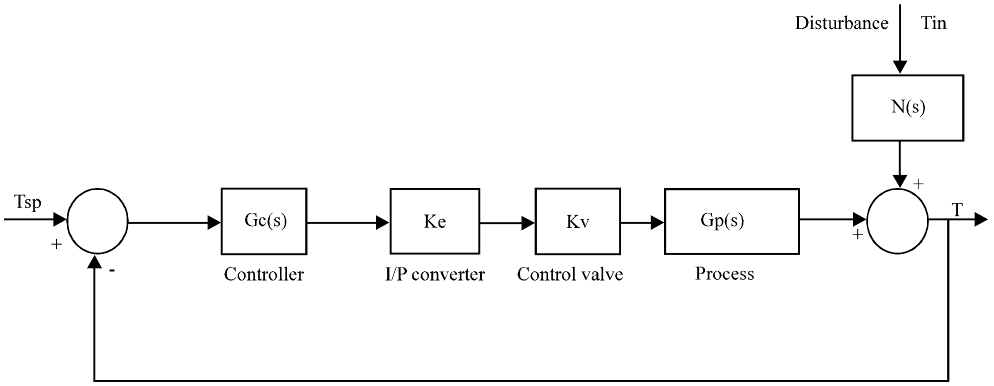

Fig. 4: Block diagram of conventional feedback control configuration for a CSTH

$$K_P = \frac{T_1}{2T_2 * K'_P};\ T_i = 4T_2 \text{ and } T_d = T_2 \tag{11}$$

Using these controller settings we can achieve desired temperature value of process fluid.

Robust cascade control: Cascade control configuration is used for enhancing the single loop performance particularly when disturbance are associated with the manipulated variable or when final control element exhibits nonlinear behavior. The frequency response method of cascade controller design is a trial and error method. It is a tedious graphical technique and also very difficult for nonlinear process (Saxena *et al*., 2002). Robust cascade control method for nonlinear interconnected process is as shown in Fig. 5. The proposed robust cascade controller design is based on SO method and Integral-Time-Absolute-Error (ITAE) criterion. The overall nonlinear transfer function model of interconnected process is separated in to two nonlinear transfer function models for kettle and jacket. During the controller design SO method is applied to the inner loop of interconnected process then optimum coefficients of closed transfer function of jacket are used for determining the values of tuning parameters in outer loop of cascade control configuration. The transfer function model of kettle and jacket are derived from their energy balance equations.

Consider the CSTH process model, when the volume, flow rate and inlet temperature are constant at their steady state values. The steady state equation of kettle and tank are given as follows:

$$\frac{V_S}{F_S}\frac{dT}{dt} = (T_{iS} - T) + \frac{UA}{F_S \rho C_P}(T_j - T) \tag{12}$$

$$\frac{V_{js}}{F_{js}}\frac{dT_j}{dt} = (T_{jins} - T_j) - \frac{UA}{F_{js}\rho_j C_{Pj}}(T_j - T) \tag{13}$$

Control engineers like to think in terms of deviation variables that is perturbations from a steady state operating condition. If we define following deviation variables:

$$y_1 = (T - T_{is});\, u_1 = \left(T_j - T_{jins}\right);\, y_2 = (T_j - T_{jins}) \text{ and } u_2 = (T - T_{is}) \tag{14}$$

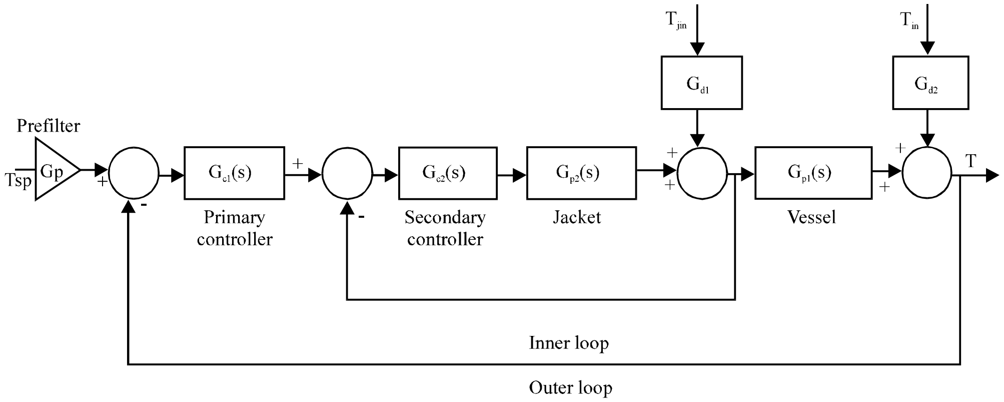

Fig. 5: Block diagram of the cascade control system for a CSTH

The above Eq. 12 and 13 can be written in the form:

$$\frac{V_S}{F_S}\frac{dy_1}{dt} = -\left[1+\frac{UA}{F_S\rho C_P}\right]y_1 + \frac{UA}{F_S\rho C_P}u_1 \tag{15}$$

$$\frac{V_{js}}{F_{js}}\frac{dy_2}{dt} = -\left[1+\frac{UA}{F_{js}\rho_j C_{Pj}}\right]y_2 + \frac{UA}{F_{js}\rho_j C_{Pj}}u_2 \tag{16}$$

Taking Laplace transform and rearranging terms:

$$G_{P1(s)} = \frac{y_{1(S)}}{u_{1(S)}} = \frac{\left(\dfrac{UA}{F_S\rho C_P}\right)}{\left(\dfrac{V_S}{F_S}s + \left[\dfrac{F_S\rho C_P + UA}{F_S\rho C_P}\right]\right)} \tag{17}$$

$$G_{P2(s)} = \frac{y_{2(S)}}{u_{2(S)}} = \frac{\left(\dfrac{UA}{F_{js}\rho_j C_{Pj}}\right)}{\left[\dfrac{V_{js}}{F_{js}}s + \left(\dfrac{F_{js}\rho_j C_{Pj} + UA}{F_{js}\rho_C C_{Pj}}\right)\right]} \tag{18}$$

The transfer function of primary process and secondary process are derived using steady state condition which are used during determining the performance of hybrid fuzzy logic controller and classical controller (Bequette, 2006). The SO method is used to design secondary controller for inner loop process after that closed loop transfer function of jacket is obtained. In robust control method, controller settings and prefilter design based on optimum coefficients of characteristics equation for ITAE criterion obtained from Table 2. The proposed robust cascade controller design is hybridization of SO method and robust PID control scheme (Dorf and Bishop, 1998).

Table 2: Optimum forms of the closed loop transfer function based on ITAE criterion

$\frac{C_{(s)}}{R_{(s)}} = \frac{a_n}{a^n + a_1 s^{n-1} + \ldots\ldots + a_{n-1}s + a_n}$
$s+\omega_n$
$s^2+1.4\,\omega_n s+\omega_n^2$
$s^3+1.75\,\omega_n\,s^2+2.15\,\omega_n^2 s+\omega_n^3$
$s^4+2.1\,\omega_n s^3+3.4\,\omega_n^2 s^2+2.7\,\omega_n^3 s+\omega_n^4$
$s^5+2.8\,\omega_n s^4+5.0\,\omega_n^2 s^3+5.5\,\omega_n^3 s^2+3.4\omega_n^4\,s+\omega_n^5$
$s^6+3.25\,\omega_n s^5+6.60\,\omega_n^2 s^4+8.60\,\omega_n^3 s^3+7.45\omega_n^4\,s^2+3.95\,\omega_n^5 s+\omega_n^6$

FUZZY PID CONTROL

In recent year, fuzzy PID controllers have been widely used for industrial process. Associated with their nonlinear gains, they are effective for linear and nonlinear systems. Because of the nonlinear property of control gains, fuzzy PID control process has a potential to improve and achieve better system performance over the conventional PID controllers. The structure of the control system with proposed fuzzy PID controller is shown in Fig. 6. The fuzzy PID controller consists of three Parallel fuzzy subcontrollers that update online the values of the proportional, integral and derivative gains. In these learning schemes, a conventional feedback controller is provided both as an ordinary feedback controller to guarantee global asymptotic stability in compact space and as an inverse reference model of the response of the controlled object (Jianling *et al*., 2007).

The architecture of the proposed hybrid control structure is consists of fuzzy PID controller and its integration with the classical PID. The essential part of control structure is the blend operation to provide the overall control signal which is the composition of the signal produced by the fuzzy controller and the one obtained from the conventional controller. It provides two distinct control modes when the state is far away or close by from the set point. When state away from the set point, the fuzzy controller is predominant to generate a quick

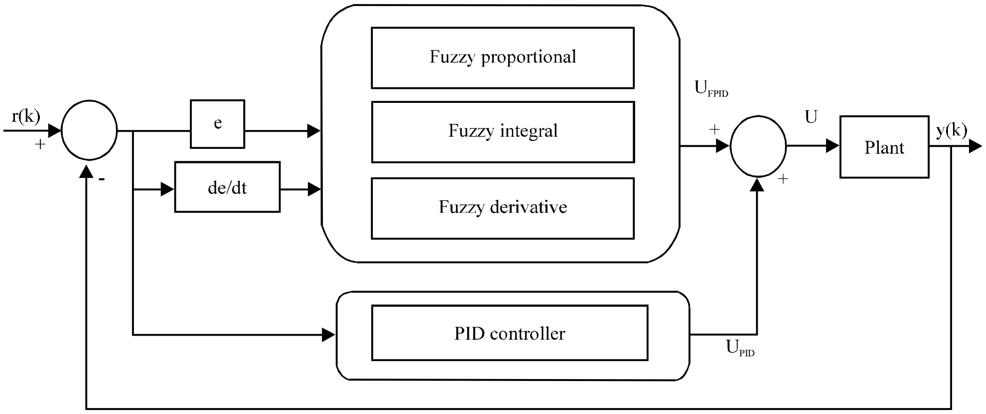

Fig. 6: Block diagram of Fuzzy PID based temperature control of CSTH

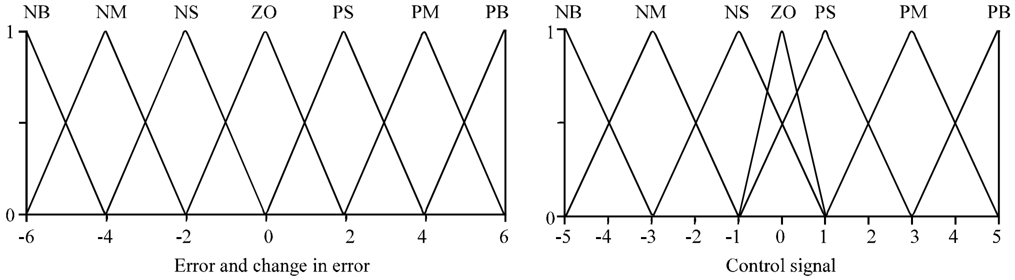

Fig. 7: Fuzzy membership function of input and output variable

response and compensate for the system nonlinearity. As the state approaches the set point, the role of the fuzzy controller diminishes and the conventional controller takes over the control responsibility to guarantee the performance accuracy. Each of the fuzzy subcontrollers has two inputs and one output is shown in Fig. 7. The inputs are error and rate of change of error while output is modificatory coefficient such as K_p, K_I and K_D in the form of fuzzy. The output of the fuzzy control decision that corresponds to each fuzzy subcontrollers is the fuzzy proportional, integral and derivative gains (Fk_p, FK_I and FK_D). Clearly Fk_p, FK_I and FK_D are direct output from the parallel fuzzy subcontrollers and are directly realized from the knowledge base and the fuzzy inference (Rubaai *et al*., 2008).

The linguistic variables of the error, the rate of change of error and modificatory coefficient are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zeros (ZO), Positive Small (PS), Positive Medium (PM), Positive Big (PB) with linguistics values of error and rate of change of error are given as {-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6} while linguistic values of modificatory coefficients are given as {-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5} their membership functions all are triangular type (Wen and Liu, 2004). The control surface of each fuzzy subcontroller is as shown in Fig. 8. The designing of the fuzzy subcontroller is nothing but the determination of the fuzzy IF-THEN inference rules. The number of fuzzy rules that are required is equal to the product of the number of fuzzy sets that make up each of the two fuzzy input variables.

For each fuzzy subcontroller described here, the input variables representing error (e) and rate of change of error (Δe) and the corresponding control signal (μ) consists of seven fuzzy sets each. Thus, total of 49 rules required. A fuzzy system with two inputs error and rate of change of error (antecedents) and a single output y (consequent) is described by collection of r linguistic IF-THEN propositions: IF e is A^k_I and Δe is A^k_2 then μ isB^k for k = 0, 1, 2,.. r.

In the above control ruleA^k_I and A^k_2 are the fuzzy sets representing the kth antecedent pairs and B^k are the fuzzy sets representing the kth consequent. The response of each fuzzy rule is weighted according to the degree of membership of its input conditions. The inference engine provides a set of control actions according to fuzzified inputs. The commonly used inference engine is the MAX-MIN method. In the rule base as shown in Table 3-5 only Zadeh's logical and which is the MIN operator is used. Since the control actions are described

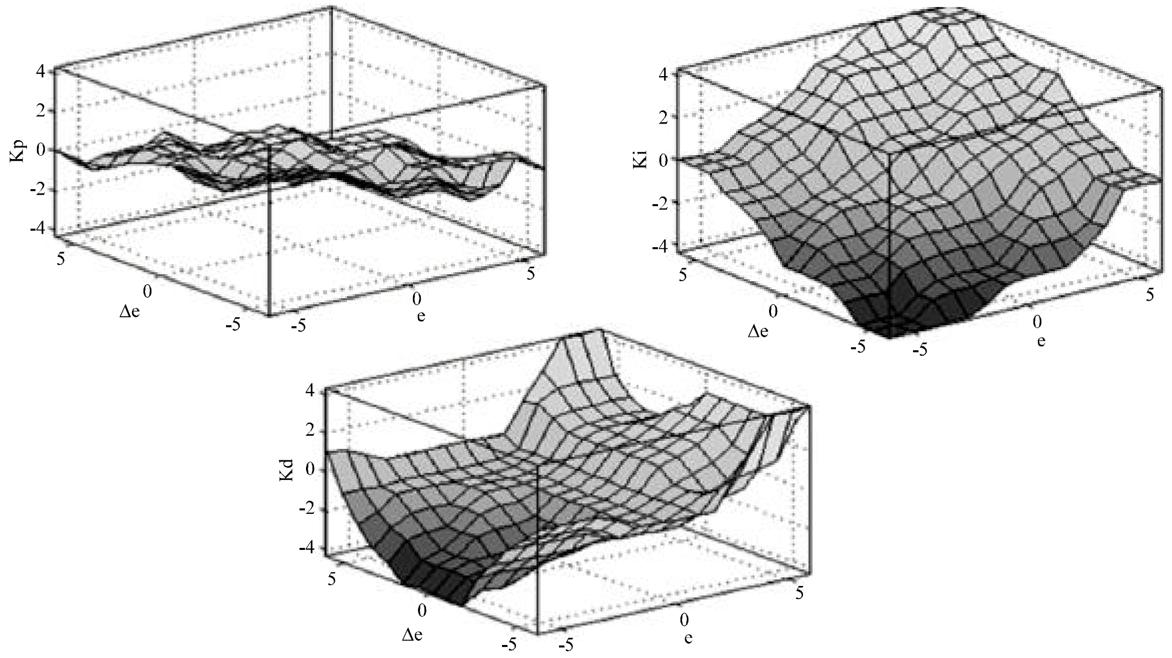

Fig. 8: Control surface of Fuzzy-P, Fuzzy-I and Fuzzy-D controller

Table 3: Fuzzy logic control rule for Kp

kp	Δe NB	NM	NS	ZO	PS	PM	PB
e							
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

Table 4: Fuzzy logic contro rule for Ki

ki	Δe NB	NM	NS	ZO	PS	PM	PB
e							
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 5: Fuzzy logic control rule for Kd

Kd	Δe NB	NM	NS	ZO	PS	PM	PB
e							
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

in a fuzzy sense, a defuzzification method is required to transform fuzzy control actions in to crisp output value of the fuzzy logic controller. The graphical analysis of two rules are shown in Fig. 9 in which the symbols $A_{11}$and A_{12} refer to the first and second fuzzy antecedents of the first rule, respectively and the symbol B_1 refers to fuzzy consequent of the first rule; the symbols A_{21} and A_{22} refer to the first and second fuzzy antecedents, respectively of the second rule and the symbol B_2 refers to the fuzzy consequent of second rule.

The minimum function in Eq. 19 is shown in Fig. 9 and arises because the antecedent pairs given in the general rule structure for this system are connected by a logical and connective as seen in control rule. The minimum membership value for the antecedent propagates through to the consequent and truncates the membership function for the consequent of each rule. This graphical inference is done for each rule:

$$\mu_{B^k}(u)=\max_k\left[\min\left[\mu_{A_1^k}(\text{input(i)}),\mu_{A_2^k}(\text{input(j)})\right]\right]$$
$$k = 1, 2, 3\ldots\ldots r \qquad (19)$$

The structure of the fuzzy subcontrollers includes two blocks such as fuzzifier and inference engine. The fuzzifier performs the function of fuzzification and converts input data from an observed input space into proper linguistic values of fuzzy sets through predefined input membership function. The fuzzy inference engine uses the appropriately designed knowledge base to

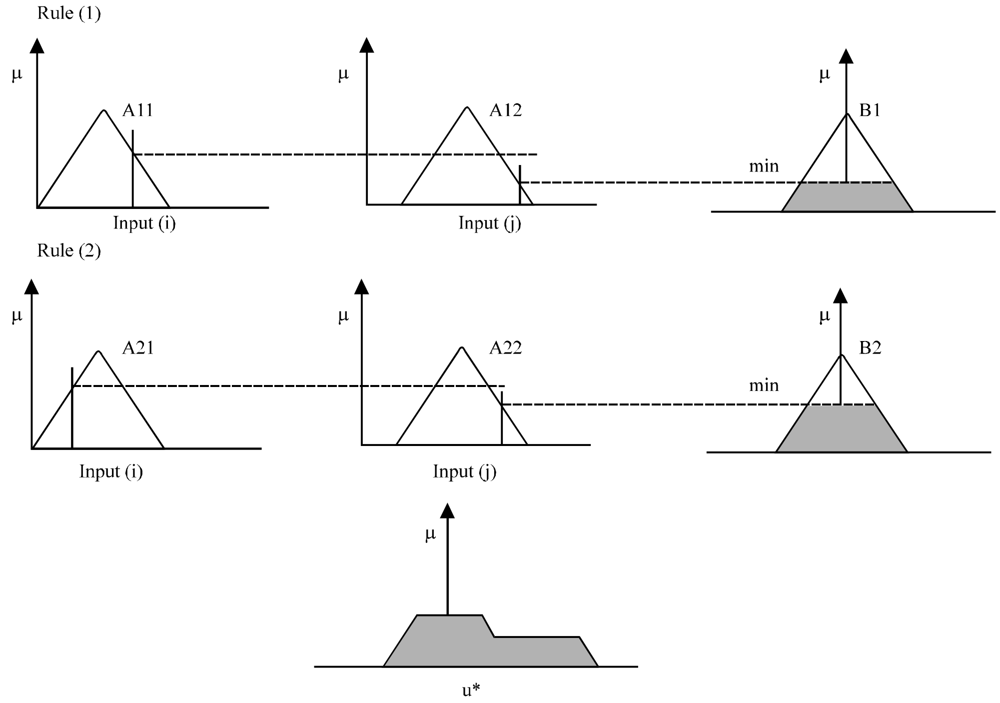

Fig. 9: Graphical analysis of two control rules

evaluate the fuzzy rules and produce an output for each rule. Subsequently the multiple outputs are transformed to a crisp output by the defuzzification inference. Once aggregated fuzzy set representing the fuzzy output variable for each subcontroller has been determined an actual crisp control decision must be made.

The process of decoding the output to produce an actual value for the control signal is referred to as defuzzification thus a fuzzy logic controller based centre-average defuzzifiers implemented (Rubaai *et al.*, 2008; Zhao and Collins, 2003).

The composed output of fuzzy PID is the combination of each fuzzy subcontroller:

$$u_{FPID}(k) = u_{FP}(k) + u_{FI}(k) + u_{FD}(k) \qquad (20)$$

where, μ_{FP} (k), μ_{FD} (k) are control signal of Fuzzy-P, Fuzzy-I and Fuzzy-D controller, respectively.

The output of each subcontroller is based on function of error and rate of change of error approximation method and their respective scaling factor to the control signals.

The scaling factors are computed experimentally on a trial and error basis. The overall fuzzy PID control equation is derived as follows:

$$u_{FPID}(k) = f_p(e,\Delta e)*G_P e(k) + f_I(e,\Delta e)*G_I\sum_{i=0}^{k} e(i)\Delta t + f_D(e,\Delta e)*G_D\frac{\Delta e(k)}{\Delta t} \quad k = 0,1,2,....... \qquad (21)$$

where, G_p, G_I and G_D are the scaling factors for the control signal. The tuning parameters Fk_p, FK_I and FK_D are the provided by the output of each fuzzy inference mechanism. Therefore the three apparent outputs of the fuzzy subcontrollers will be:

$$\left.\begin{aligned} FK_P &= f_P(e,\Delta e)*G_P \\ FK_I &= f_I(e,\Delta e)*G_I \\ FK_D &= f_D(e,\Delta e)*G_D \end{aligned}\right\} \qquad (22)$$

$$u_{FPID}(k) = FK_P*e(k) + FK_I*\sum_{i=0}^{k} e(i)\Delta t + FK_D*\frac{\Delta e(k)}{\Delta t} \quad k = 1,2,3,.... \qquad (23)$$

The classical linear PID controller in its discrete form can be characterized as:

$$u_{PID}(k) = K_P*e(k) + K_I*\sum_{i=0}^{k} e(i)\Delta t + K_D*\frac{\Delta e(k)}{\Delta t} \qquad (24)$$

where, K_p, K_I and K_D are constant gains. The composed output of proposed intelligent hybrid fuzzy PID controller:

$$u(k) = u_{FPID}(k) + u_{PID}(k) \tag{25}$$

$$\begin{aligned} u(k) &= (K_P + FK_P) * e(k) + (K_I + FK_I) \\ &* \sum_{i=0}^{k} e(i)\Delta t + (K_D + FK_D) * \frac{\Delta e(k)}{\Delta t} \end{aligned}$$

$$\mu(k) = (FK_P)_{eq} * e(k) + (FK_I)_{eq} * \sum_{i=0}^{k} e(i)\Delta t + (FK_D)_{eq} * \frac{\Delta e(k)}{\Delta t} \tag{26}$$

Where $(Fk_p)_{eq}$, $(FK_I)_{eq}$ and $(FK_D)_{eq}$ are defined to be the equivalent proportional, integral and derivative gains. The control signal $\mu(k)$ is used to achieve desired plant output (Rubaai *et al*., 2008). The resultant control signal from hybrid fuzzy PID control structure is provided from blending mechanism of conventional controller with parallel form of fuzzy subcontrollers such as fuzzy-P, fuzzy-I and fuzzy-D which gives desired response of the nonlinear process but desired response not obtained when various disturbances are to be considered. So that purpose fuzzy cascade control approach is taken in to account for enhancing single loop performance with eliminating disturbance effects on nonlinear process.

FUZZY CASCADE CONTROL

Cascade control systems or subsidiary controls with major and minor control loops can be realized in situation where additional measured variable can be used for feedback from the signal path in between manipulated variable and the control variable. By connecting additional variables to the single loop we can improve the response of system. These additions to the single loop lead to interconnected control system. Fuzzy cascade control is one of the most useful concepts in advance control strategy. A fuzzy cascade control structure has two fuzzy logic controllers with output of the primary fuzzy logic controller changing the set point of the secondary fuzzy logic controller. The output of secondary fuzzy logic controller goes to the final control element to achieve desired temperature of vessel. Fuzzy PID act as primary controller in outer loop while fuzzy PI used in inner loop as a secondary controller. The similar control architecture is used in fuzzy cascade controller application which is already implemented in intelligent hybrid Fuzzy PID control. Both primary and secondary fuzzy logic controller has two inputs error and rate of change of error and output is control signal. The basic control structure of fuzzy cascade control configuration is as shown in Fig. 10. The control equation of primary and secondary controller are given as follows:

$$u_1(k) = (FK_p)_{eq} * e(k) + (FK_I)_{eq} * \sum_{i=0}^{k} e(i)\Delta t + (FK_D)_{eq} * \frac{\Delta e(k)}{\Delta t} \tag{27}$$

$$\mu_2(k) = (FK_p)_{eq} * e(k) + (FK_I)_{eq} * \sum_{i=0}^{k} e(i)\Delta t \tag{28}$$

Fuzzy PI controller generates an incremental control action Δu from the error e and the change in error Δe. In fuzzy PI controller, the outputs of the fuzzy logic reasoning are the proportional and integral gain instead of the incremental control signal. The control signal is generated according to the on line tuning of proportional and integral gains. There are two fuzzy logic reasoning systems included in the design, one of them has two inputs; error and rate of change of error with output is Fk_p, the other one has the same inputs but output is FK_I. Linguistic values of error, change in error and modificatory coefficient with their linguistic variables are

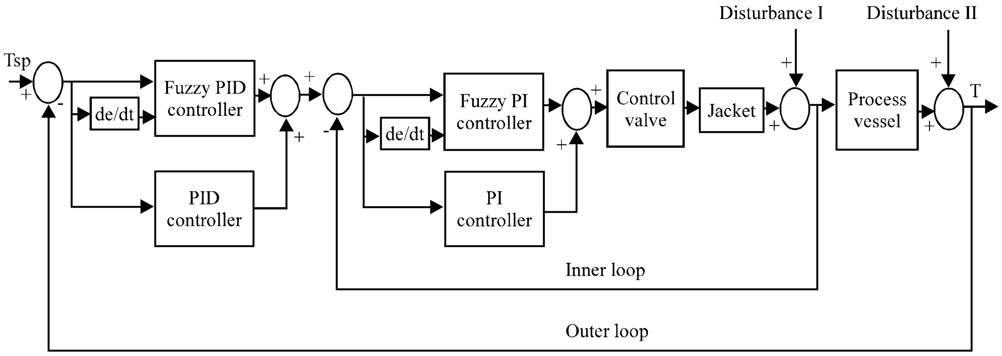

Fig. 10: Block diagram of a fuzzy cascade control configuration of CSTH

shown in Fig. 7. Their membership functions are triangular type. In the design of fuzzy PI controller where each of the fuzzy proportional and fuzzy integral gains are tuned based on 49 rules, respectively (Zhao and Collins, 2003). The fuzzy PID as a primary fuzzy logic controller which is mainly composed of three fuzzy subcontrollers such as fuzzy-P, fuzzy-I and fuzzy-D which works parallel with conventional feedback PID controller. Each fuzzy subcontroller has two inputs and one output such as FK_p, FK_I and FK_D (Stephanopoulos, 2004). The tuning of modificatory coefficients are mainly depends on rules as shown in Table 3-5. Fuzzy PID controller translates the error and rate of change of error in to discrete values in fuzzy fields through scaling factors. Three controlled fuzzy variables are obtained from fuzzy control rule base which is developed from expert knowledge. The knowledge can be expressed in the form of if-then rules; then it summarize in a Fuzzy Association Memory (FAM) table. Control variable ultimately applied to the system is precise so that we translate the three controlled variable in to precise variable as a modificatory parameters (Wen and Liu, 2004).

RESULTS AND DISCUSSION

In order to evaluate the performance of proposed hybrid fuzzy PID and hybrid fuzzy cascade controller; Various control strategies have been tested and compared in terms of ISE on simulated process. The performance of developed advance control strategies has also been compared with optimize PID control and robust cascade control schemes. To evaluate the performance of the controllers we considered the transfer function model of CSTH process with their other elements in classical control technique as well as in hybrid fuzzy logic control method.

To study the performance of the controllers, firstly the tracking performances of the controller with respect to different set point were obtained. For the set point tracking, following set points were considered: SP1 = 40 for $0 \le t \le 60$; SP2 = 20 for $60 \le t \le 120$ and SP3 = 30 for $120 \le t \le 180$. The performance of optimize PID control, robust cascade control, Fuzzy PID based control and Fuzzy cascade control for the system described by the transfer function model are shown in Fig. 11. To study the robustness of proposed hybrid fuzzy cascade and robust cascade controller under the influence of the various disturbances which are added to the plant input for the time interval $60 \le t \le 100$ then output response of inter connected process are shown in Fig. 12-17. From Table 6,

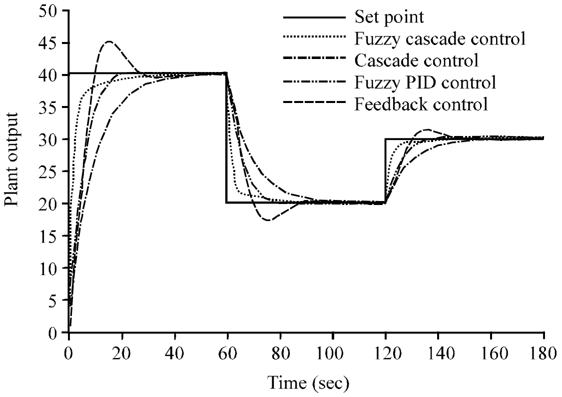

Fig. 11: Set point tracking performance of CSTH process

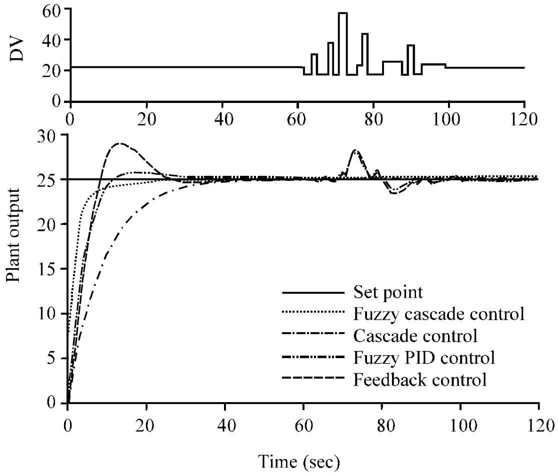

Fig. 12: Response of CSTH process under the influence of disturbance (VI); DV = Disturbance value

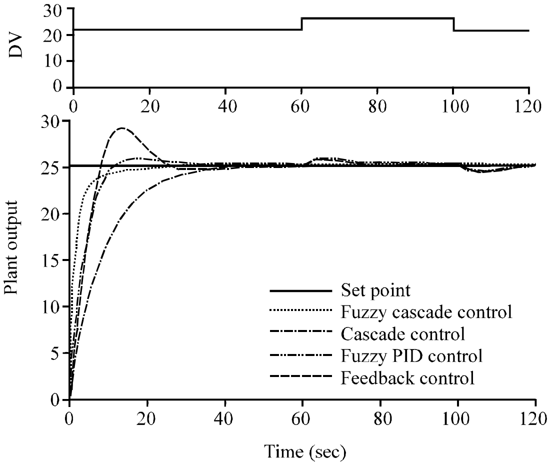

Fig. 13: Response of CSTH process under the influence of disturbance (I) Disturbance (II): Step change (20% decreasing in set point); DV = Disturbance value

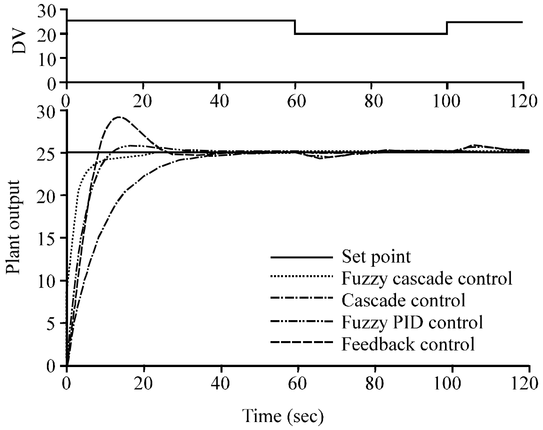

Fig. 14: Response of CSTH process under the influence of disturbance (II); Disturbance (III_: Sinusoidal disturbance (II); DV = Disturbance Value

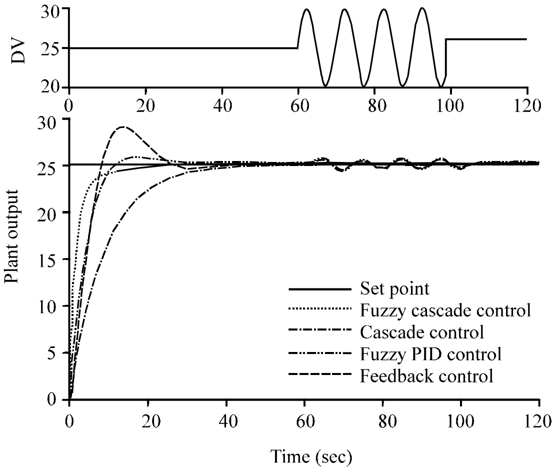

Fig.15: Response of CSTH process under the influence of disturbance (III) Disturbance (IV): Impulse disturbance; DV = Disturbance value

it is shown that the ISE values of hybrid fuzzy cascade control and robust cascade control for different set points are comparatively less than fuzzy PID control and conventional feedback control technique. It is observed that the system output response have tracked the desired output at different set points. The effect of various disturbances on CSTH process can be eliminated using hybrid cascade control and robust cascade control structure. From set point tracking performance and the ISE's values in Table 7 we concluded that hybrid fuzzy cascade is comparatively better than another controller method. The tracking performance of different controllers can be checked through giving sinusoidal change in set point. The sinusoidal response of CSTH process is as

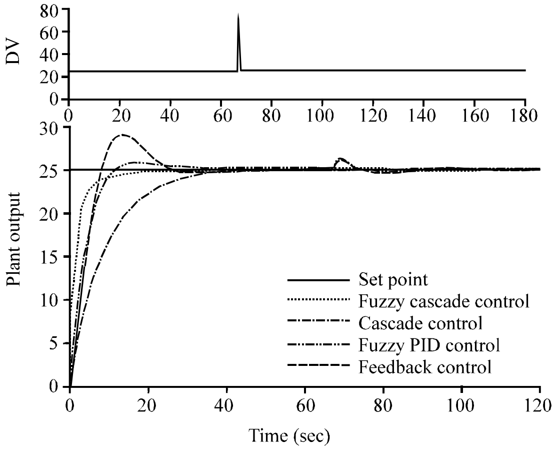

Fig. 16: Response of CSTH process under the influence of disturbance (IV); Disturbance (V): sampled gaussian noise; DV = Disturbance value

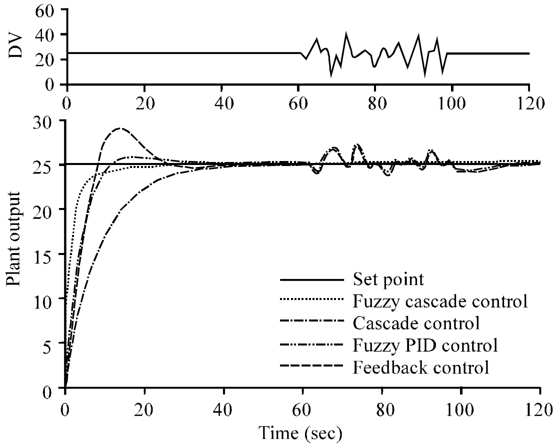

Fig. 17: Response of CSTH process under the influence of disturbance (V) Disturbance (VI): Pseudorandom Noise; DV = Disturbance value

Table 6: A Disturbance rejections of controllers in terms of the ISE

	Set point 0-25					
	Disturbance models					
Controller methods	I	II	III	IV	V	VI
Fuzzy cascade control	0.1363	0.0363	0.2531	0.1531	0.2035	0.2035
Conventional cascade control	0.1832	0.0832	0.2699	0.1699	0.2491	0.2204
Fuzzy PID control	0.2327	0.1867	0.3045	0.3024	0.3076	0.3050
Conventional feedback control	0.2659	0.2159	0.3082	0.3050	0.3095	0.3082

Table 7: Performance comparison of controllers in terms of the ISE

	Set point		
Controller methods	0-40	40-20	20-30
Fuzzy cascade control	0.5841	0.2035	0.9106
Conventional cascade control	1.4345	0.2655	1.8009
Fuzzy PID control	1.4159	0.2159	1.0505
Conventional feedback control	2.0177	0.3045	1.5673

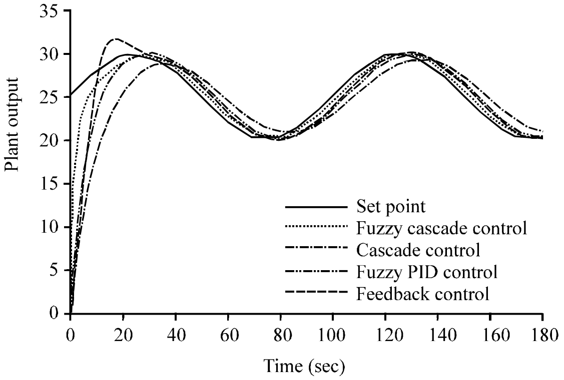

Fig. 18: Sinusoidal response of CSTH process

shown in Fig. 18. Hybrid control approach gives best tracking performance with guarantee of global asymptotic stability in compact space.

CONCLUSION

Hybrid fuzzy PID and Hybrid fuzzy cascade controllers are developed and the performance has been compared with classical control. Simulated results have shown excellent tracking performance of the proposed hybrid fuzzy PID and fuzzy cascade control than the classical control techniques on the model of the CSTH. The main purpose for proposing the hybrid fuzzy PID and hybrid fuzzy cascade controller is to improve control performance of many industrial plants that are already controlled by the PID and cascade type controllers.

The structure of fuzzy PID consist of parallel structure of fuzzy subcontrollers such as Fuzzy-P, Fuzzy-I and Fuzzy-D then its integration with conventional PID controller for improving set point tracking performance.

The similar structure is implemented for Fuzzy PI controller. These two controllers are used as primary and secondary controllers in Fuzzy cascade control for regulating the temperature of process vessel in the influence of continuous unknown disturbance. Future research will be focused on the real time implementation of the advance controllers.

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