A Comparative Analysis of Various Control Strategies Implemented on Heat Exchanger System: A Case Study

Subhransu Padhee and Yaduvir Singh

Abstract— **In this research paper, an intelligent fuzzy PID controller is developed to control the outlet temperature of a shell and tube heat exchanger. The aim of the proposed controller is to regulate the temperature of the outgoing fluid to a desired level in the shortest possible time irrespective of load and process disturbances, equipment saturation and nonlinearity. The fuzzy PID controller provides a satisfactory performance in both steady state and transient state and overcomes the drawbacks of conventional PID controller and feed-forward controller. The developed fuzzy PID controller has demonstrated 84% improvement in the overshoot and 74% improvement in settling time from the classical controller. Also control accuracy is 100% as steady state error becomes zero.**

***Index Terms*—Feed-forward controller, Fuzzy PID controller, PID controller, Shell and tube heat exchanger**

I. INTRODUCTION

In practice, all chemical processes involve the production or absorption of energy in the form of heat. Heat exchanger is commonly used in industrial chemical processes to transfer heat from a hot liquid through a solid wall to a cooler fluid [1]. A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact [3]. There are different types of heat exchanger used in the industry but most of the industry use shell and tube type heat exchanger system. It consists of parallel tubes enclosed in a shell. There is a variety of application of heat exchanger system. Some of the applications include HVAC (heating, ventilation, and air conditioning), electronic cooling, refrigeration and air conditioning, manufacturing, and power generation. In each of these cases, the purpose of the heat exchanger is to maintain a specific temperature condition, which is achieved by controlling the exit temperature of one of the fluids in response to variations of the operating conditions [5].

The concept of intelligent control lies with the fact that human intelligence is imbibed in to the controller architecture so that human behavior can be emulated in the control decision. Human expert knowledge is based upon heuristic information gained in relation to the operation of the plant or process, and its inherent vagueness ("fuzziness") offers a powerful tool for the modeling of complex systems. The fuzzy logic controller provides an algorithm, which converts the expert knowledge into an automatic control strategy. Fuzzy logic is capable of handling approximate information in a systematic way and therefore it is suited for controlling non linear systems and is used for modeling complex systems where an inexact model exists or systems where ambiguity or vagueness is common. The fuzzy control systems are rule-based systems in which a set of fuzzy rules represent a control decision mechanism to adjust the effects of certain system stimuli. With an effective rule base, the fuzzy control systems can replace a skilled human operator. The rule base reflects the human expert knowledge, expressed as linguistic variables, while the membership functions represent expert interpretation of those variables.

This research paper considers a shell and tube heat exchanger and builds a SISO model of the system with the help of experimental data available. This system also takes in to account different disturbance elements and transportation delay. First of all, a classical PID controller is implemented in a feedback control loop so as to obtain the control objectives. To further optimize the control performance, feed-forward controller is used in conjunction with the PID controller. In classical control methods different performance indices were calculated for feedback and feedback plus feed-forward control loops to achieve the desired robustness and system stability. Auto-tuning of PID controllers is also implemented and simulated in this paper. To achieve the desired control objective and implement human intelligence in controller architecture a fuzzy logic based PID controller is designed and implemented. All the system level simulation and controller design in this paper are carried out in Simulink. A comparative study of all the control performance is evaluated in this paper.

II. CASE STUDY

A typical interacting chemical process for heating consists of a chemical reactor and a shell and tube heat exchanger system. The process fluid which is the output of the chemical reactor is stored in the storage tank. The process fluid considered in this case is $Al_2(SO_4)_3$+H_2SO_4+Alum. The storage tank supplies the fluid to the shell and tube heat exchanger system. The heat exchanger heats up the fluid to a desired set point using super heated steam at 180°C supplied from the boiler. The storage tank supplies the process fluid to the heat exchanger system using a pump and a non returning

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valve. The super heated steam comes from the boiler and flows through the tubes, whereas, the process fluid flows through the shells of the shell and tube heat exchanger system. After the steam heats up the process fluid, the condensed steam at 100° C goes out of the heat exchanger system. There is also a path for non-condensed steam to go out of the shell and tube heat exchanger in order to avoid blocking of the heat exchanger.

Different assumptions have been considered. The first assumption is that the inflow and the outflow rate of fluid are same, so that the fluid level is maintained constant in the heat exchanger. The second assumption is the heat storage capacity of the insulating wall is negligible. In this feedback process control loop, the controller is reverse acting, the valve used is of air to open (fail-close) type. A thermocouple is used as the sensing element which is implemented in the feedback path of the control architecture. The temperature of the outgoing fluid is measured by the thermocouple and the output of the thermocouple (voltage) is sent to the transmitter unit, which eventually converts the temperature output to a standardized signal in the range of 4-20 mA. This output of the transmitter unit is given to the controller unit. In this heat exchanger system a PID controller has been taken as the controlling unit. The PID controller implements the control algorithm, compares the output with the set point and then gives necessary command to the final control element via the actuator unit. The actuator unit is a current to pressure converter and the final control unit is an air to open (fail close) valve. The actuator unit takes the controller output in the range of 4-20 mA and converts it in to a standardized pressure unit, i.e in the range of 3-15 psig. The valve actuates according to the controller decisions.

There can be two types of disturbances in this process, one is the flow variation of input fluid and the second is the temperature variation of input fluid. But in practice the flow variation of input fluid is a more prominent disturbance than the temperature variation in input fluid. So, in feed forward control loop the input fluid flow is measured and the disturbance in the flow is controlled using a feed forward controller. The output of the feedback and the feed forward controller is added and the resultant output is given to the control valve. With the addition of feed forward controller the control performance is optimized.

III. PROBLEM STATEMENT

In this section we have developed a block diagram of these control loops and modeled the heat exchanger system, actuator, valve, sensor using the experimental data available. The transfer function model of the individual systems are generated which in turn combined to acquire the transfer function of the whole system.

A. Experimental Data

Exchanger response to the steam flow gain	50° C/(kg/sec)
Time constants	30 sec
Exchanger response to variation of process fluid flow gain	1° C/(kg/sec)
Exchanger response to variation of process temperature gain	3° C/° C
Control valve capacity	1.6 kg/sec of steam
Time constant of control valve	3 sec
The range of thermocouple	50° C to 150° C
Time constant of thermocouple	10 sec

From the above experimental data the transfer function model of the system is derived.

Transfer function of process	$\frac{50e^{-sT_d}}{30s+1}$
Gain of valve	0.133
Transfer function of valve	$\frac{0.133}{3s+1}$
Gain of I/P converter	0.75
Transfer function of disturbance variables (flow and temperature disturbances respectively)	$\frac{1}{30s+1}, \frac{3}{30s+1}$
Transfer function of thermocouple	$\frac{0.16}{10s+1}$

B. PID Controller

The characteristic equation (1+G(s)* H(s) =0) in this case is obtained as below.

$900s^3+420s^2+43s+0.798K_c+1=0$ (1)

Applying Routh stability criterion in eq. (1) gives K_c as 23.8

Auxiliary equation $420s^2+0.798K_c+1=0$ (2)

From eq. (2) $\omega=0.218$ and $T=28.79$

PID controller in continuous time is

$$u(t) = b + K_c\left(e(t) + \frac{1}{\tau_i}\int_0^t e(t)dt + \tau_d \frac{de(t)}{dt} \right) \tag{3}$$

The PID controller is traditionally suitable for second and lower order systems. It can also be used for higher order plants with dominant second order behaviour. The Ziegler-Nichols (Z-N) methods rely on open-loop step response or closed-loop frequency response tests. A PID controller is tuned according to a table based on the process response test. According to Zeigler-Nichols frequency response tuning criteria

$K_p = 0.6K_c$, $\tau_i = 0.5T$ and $\tau_d = 0.125T$

For the PID controller in the heat exchanger, the values of tuning parameters obtained are $K_p=14.28$, $\tau_i=14.395$, $\tau_d=3.59$ and P= 23.8, I= 1.65, D=85.442

C. Feedback and Feed-forward Controller

In feed forward controller we have tried to regulate the flow disturbance of the input fluid. $G_p(s)$ is the transfer function of the process where as $G_d(s)$ is the transfer function of flow disturbance.

$$G_p(s) = \frac{5}{90s^2+33s+1},\ G_d(s) = \frac{1}{30s+1}$$

The transfer function of the feed-forward controller is

$$G_{cf}(s) = \frac{-G_d(s)}{G_p(s)} \tag{4}$$

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$$G_{cf}(s)=\frac{-18s^2-6.6s-0.2}{(30s+1)(\lambda s+1)} \qquad (5)$$

Here, ‘λ’ is the filter parameter, whose range is from 0 to 1. It has been used to make the transfer function semi proper.

D. *Hybrid Fuzzy PID Controller*

PID controller is a standard control structure for classical control theory. But the performance is greatly distorted and the efficiency is reduced due to nonlinearity in the process plant. The fuzzy PID controllers are the natural extension of their conventional version, which preserve their linear structure of PID controller. The fuzzy PID controllers are designed using fuzzy logic control principle in order to obtain a new controller that possesses analytical formulas very similar to digital PID controllers. Fuzzy PID controllers have variable control gains in their linear structure. These variable gains are non linear function of the errors and changing rates of error signals. The main contribution of these variable gains in improving the control performance is that they are self-tuned gains and can adapt to rapid changes of the errors and rate of change of error caused by time delay effects, nonlinearities and uncertainties of the underlying process [2].

In the simulation the input variables of the fuzzy PID controllers are error e(t) and rate of change of error Δe(t). The output variable is the controller output to the actuator u(t). The variable ranges are pre assigned as $-1< e(t) <1$, $-1< \Delta e(t) <1$, and $-1< u(t)<1$

TABLE I

LINGUISTIC VARIABLES FOR FUZZY PID CONTROLLER

Error e(t)		Change in error Δe(t)		Controller output u(t)	
NB	Negative Big	NB	Negative Big	NB	Negative Big
NM	Negative Medium	NM	Negative Medium	NM	Negative Medium
NS	Negative Small	NS	Negative Small	NS	Negative Small
ZO	Zero	ZO	Zero	ZO	Zero
PS	Positive Small	PS	Positive Small	PS	Positive Small
PM	Positive Medium	PM	Positive Medium	PM	Positive Medium
PB	Positive Big	PB	Positive Big	PB	Positive Big

Designing a good fuzzy rule base is the key to obtain satisfactory control performance for a particular operation. Classical analysis and control strategy are incorporated in the rule base. The rule base used in simulation is summarized in Table II. Each rule has the form IF e(t) is NB AND Δe(t) is NB THEN u(t) is NB. The control literature has worked towards reducing the size of the rule base and optimizing the rule base using different optimization techniques like GA, PSO for intelligent controller. At last defuzzified output is obtained from fuzzy inputs. In this research work centroid method of de fuzzification is used. It is given as below.

$$Z^{*}=\frac{\int \mu_c(z) * z\,dz}{\int \mu_c(z)\,dz} \qquad (6)$$

TABLE II

IF-THEN RULE BASE FOR FUZZY PID CONTROLLER

U(t)		e(t)						
		NB	NM	NS	ZO	PS	PM	PB
Δe(t)	NB	NB	NB	NB	NB	NM	NS	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS	PM	PB	PB
	PM	NS	ZO	PS	PM	PB	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

IV. SIMULATION AND TESTING

The simulations for the different control mechanism discussed are carried out in Simulink and the simulation results have been obtained.

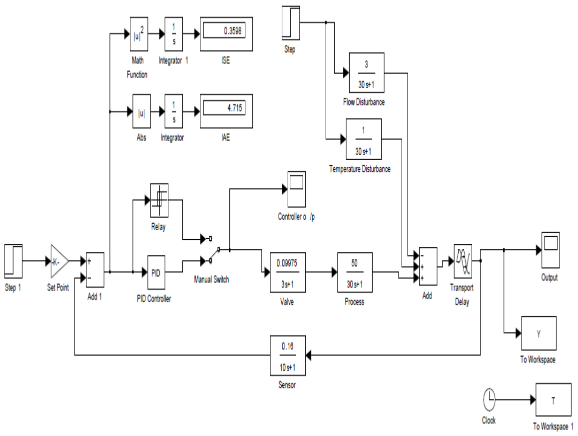
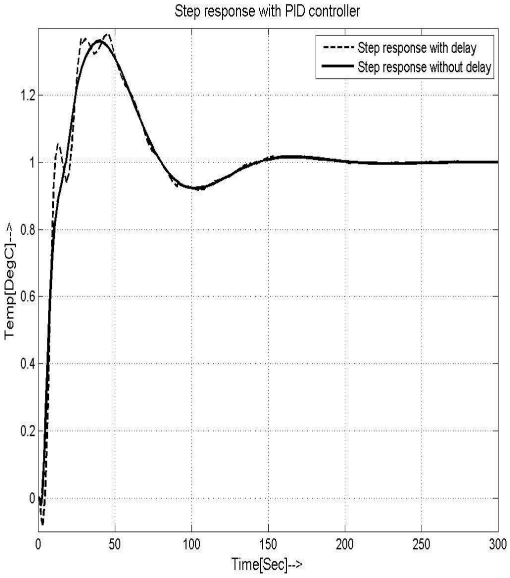
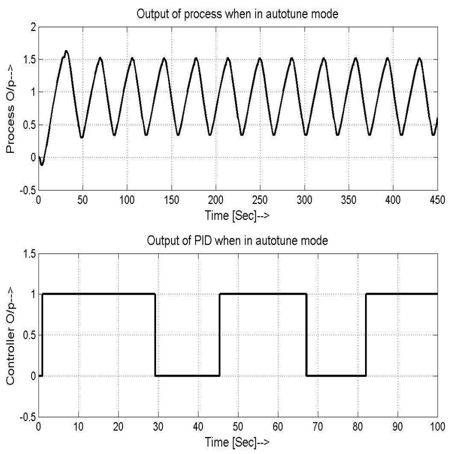


Fig. 1. Simulink model of process with feedback PID controller



(a)



(b)

Fig. 2. (a) Step response of feedback controller (b) Response of PID controller and process in auto-tune mode.

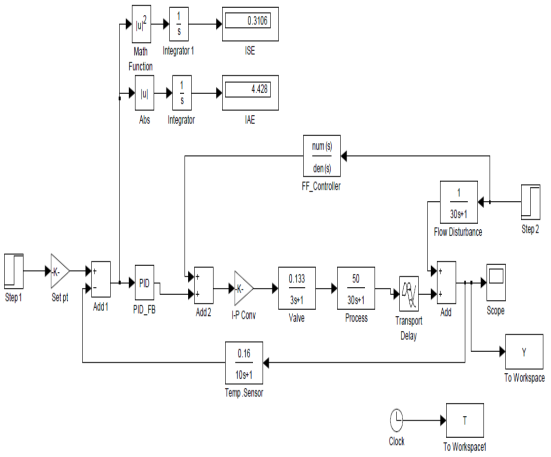


Fig. 3. Simulink model of process with feedback and feed-forward controller

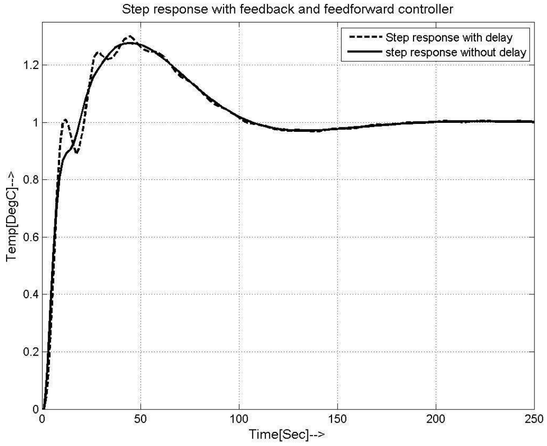


Fig. 4. Step response of process with feedback and feed-forward controller

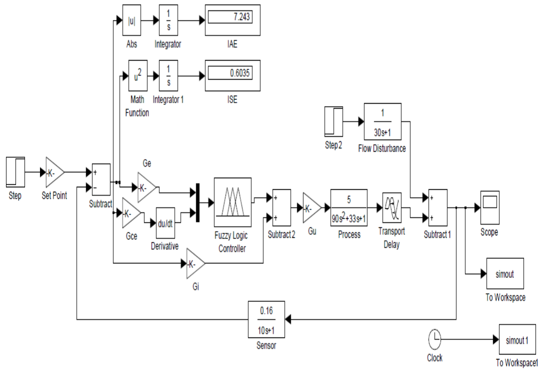


Fig. 5. Simulink model of fuzzy PID controller

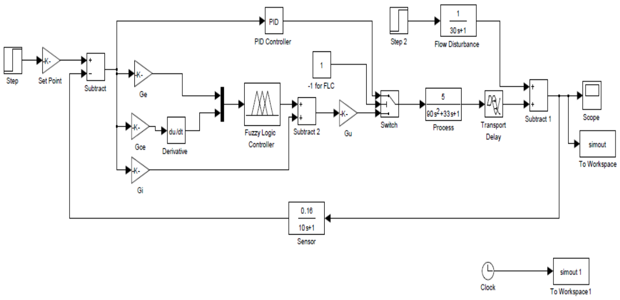


Fig. 6. Simulink model of hybrid fuzzy PID controller

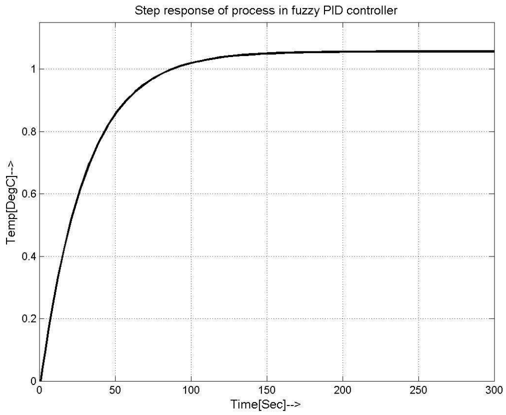


Fig. 7. Step response of process with hybrid fuzzy PID controller

V. RESULTS AND OBSERVATION

The simulation results clearly shows that the fuzzy PID controller gives a much better control of temperature rather than classical PID controller and PID controller in conjunction with feed forward controller. To evaluate the performance of the different controllers we have considered two parameters of the step response of the system. The first parameter is the maximum overshoot and the 2nd parameter is the settling time.

In all the three controllers these two parameters are evaluated and a comparative study of their performance has been shown in the table below.

TABLE III

COMPARISION OF DIFFERERNT PARAMETERS IN CONTROLLERS

S.No	Parameters	Feedback PID	Feedback plus feed forward controller	Fuzzy PID controller
1	Overshoot	36.11%	28.4%	5.63%
2	Settling time	118.2 sec	95 sec	30 sec

TABLE IV

COMPARISION OF PERFORMANCE INDICES VALUES OF CONTROLLERS

S.No	Parameters	Feedback PID	Feedback plus feed forward controller	Fuzzy PID controller
1	IAE	4.71	4.428	7.243
2	ISE	0.3598	0.312	0.6035

From the above observations it is clear that in conventional PID controller in feedback loop the heat exchanger produces an overshoot is 36%. To compensate this kind of high overshoot we implemented a feed-forward controller in conjunction with the conventional PID. By implementing this method the system overshoot was reduced to 28%. Though the overshoot has some what decreased we can further reduce the overshoot by implementing fuzzy logic based PID controller. By implementing hybrid fuzzy PID controller in the feedback loop the overshoot reduces to 5.6%.

In feedback controller the settling time was 118 sec where as in feed forward plus feedback controller the settling time decreases to 95 sec, and in hybrid fuzzy PID controller the settling time decreases to 30 sec.

Table 4 shows the performance indices of different controllers. IAE and ISE of hybrid fuzzy PID controller are high compared to other classical controller which indicates the robust control of the controller.

From these observations it is clear that fuzzy logic controller is a much better option for control rather than conventional feedback and feedback plus feed-forward controller.

VI. CONCLUSION

This paper emphasizes on the temperature control aspect of the shell and tube heat exchanger system. To efficiently control the temperature we have designed three kinds of controllers and evaluated their performance according to two basic parameters. It is observed that intelligent controller like fuzzy PID controller gives a much better response than any other conventional controller.

A lot of further works can be done in this current proposal. A GA based fuzzy PID controller can be developed which can increase the efficiency of the fuzzy PID controller. Instead of the conventional feed forward structure a neural network based multi layer feed forward architecture can be implemented.

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