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Control of Heat Exchanger Using Hybrid Fuzzy-Pi

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ABSTRACT

In this paper the potentials of fuzzy logic based control techniques are explored by applying standard Mamdani based control methodology and a type of hybrid Fuzzy-PI controller for the control of hot water outlet temperature of a co-current shell and tube heat exchanger. Standard Fuzzy Logic Controllers (FLCs) need more information to compensate for nonlinearities when operating conditions change. Here a hybrid of conventional and fuzzy controller has been used to determine the controller actions for the dynamic plant subjected to change in operating conditions. The real time implementation of hybrid Fuzzy-PI controller is discussed and compared with a standard FLC.

I. INTRODUCTION

Heat exchangers are devices in which thermal energy is exchanged between two fluids. It forms integral equipment in most of the process industries, providing a spectrum of functions including cooler, reboiler, heater, chiller, condenser etc. The main purpose of control in heat exchangers is to regulate the outlet temperature of one of the fluids flowing inside them. The complexity in control of heat-exchanger finds its roots in its highly nonlinear dynamics and particularly to the variable steady-state gain and the time constant with the flow rate of the process fluid [1]. A conventional PID controller with fixed parameters may usually derive poor control performance, since the gain and the time constant of the system change with the operating conditions [2]. The controller settings well suited for one operating point may not work well at other operating points. Similar case exists with load disturbances; this incapability of conventional controllers necessitates the development of better algorithms.

Intelligent controllers like fuzzy logic controllers (FLC) thus come into picture that uses the human knowledge and experience to overcome the aforementioned limitations thereby providing a reasonable and effective alternative to classical controllers. The strength of fuzzy logic controllers lies in its ability to represent the linguistic description of human expertise in controlling the process as fuzzy rules or relations. The inference mechanism then uses this knowledge as the base to determine the control actions. A standard fuzzy logic control however cannot react to changes in operating conditions [3]. The FLCs need more information to compensate nonlinearities when operating conditions change. It is seen that a hybrid control methodology based on conventional and fuzzy controller shows greater potential in such situations [4].

In this work, an attempt has been made to design a hybrid Fuzzy-PI controller for a co-current shell and tube heat exchanger. The effectiveness of the designed controller is tested on a laboratory scale heat exchanger. The controller is implemented in real time environment using the MATLAB. The performance of the designed controller has been compared with those obtained using a standard fuzzy controller experimentally.

II. PROCESS DESCRIPTION

Shell and tube heat exchangers are probably the most common type of heat exchangers applicable for a wide range of operating temperatures and pressures. The shell and tube heat exchanger setup used for study is shown in the Fig.1.

Fig. 1: Experimental Setup

The system consists of 37 copper tubes of 750 mm length with a single pass arrangement. The experiment is carried out in a single phase, both the fluid streams being water. The hot fluid (water) flows from the process tank and passes through the tube-side of the heat exchanger. Cold fluid (water) flows from the reservoir tank into the shell side of the heat exchanger. The disturbance tank is provided to study the performance of designed controllers for disturbance rejection. Thyristor drives are provided to regulate the heater inputs in order to maintain the desired temperature in process and disturbance tank. The cold and hot water inlet flow to the shell and tubes respectively can be manipulated using pneumatic control valves. The inlet and outlet temperatures of the shell and tube side fluid are measured using RTDs.

The hot water outlet temperature is considered as the process variable and the cold water flow rate to the shell side is treated as the manipulated variable. The flow rate of the hot water is treated as disturbance variable. The hot water inlet temperature is maintained constant with a + 0.5^{o}C variation using an inbuilt digital PID controller. The cold water is supplied at the room temperature. The inlet flow of the cold water can be varied in the range of 0-350 LPH and that of hot water between 0-250 LPH. All the sensor and actuators are interfaced with a 16 bit data acquisition system (Advantech ADAM 5000 series hardware). The module consists of 8 analog inputs and 4 analog output channels. Communication standard used is RS232. The specifications of the heat-exchanger are tabulated in Table 1.

TABLE 1: SPECIFICATIONS OF HEAT-EXCHANGER

SHELL SPECIFICATIONS		TUBE SPECIFICATIONS	
Body Material	SS	Body Material	Copper
Diameter mm	150	Diameter 4.6mm(ID) 6mm(OD)	
Length mm	800	Length mm	750

III. CONTROLLER DESIGN

Fuzzy Logic Controller (FLC)

The problem of control is also one of decision making, viz., given the observation of the state of the process to decide from encoded knowledge what action to take. Knowledge based systems and in particular rule-based approaches are ideally suited for such a decision making task. The fuzzy controller is one such simple rule-based control strategy. The most suitable applications of fuzzy control are qualitative requirement for a satisfactory control action and these qualitative requirements can be easily stated as fuzzy logic rules [5]. Thus, often a rule-based control paradigm may produce better controllers than based on analytic control theory paradigm.

The design of fuzzy logic controller is attempted in real time for the laboratory scale heat exchanger using Mamdani method [6].The fuzzy controller is designed with two input variables, temperature, error in temperature and one output variable i.e. current which is given to the current to pressure (I/P) converter which in turn will vary the position of control valve thus changing the flow rate of the cold water. The universe of discourse for temperature, error in temperature and output variable are scaled from (30-60˚C), (-30˚C to +30˚C) and (4-20) mA respectively. The fuzzy membership functions for the input and the output variables are defined using the triangular function equation as shown in Figs. 2-4. The implication scheme employed is Min-max and the defuzzification is done by using the method of heights. The Fuzzy Associative Memory (FAM) used for control is shown in Table 2.

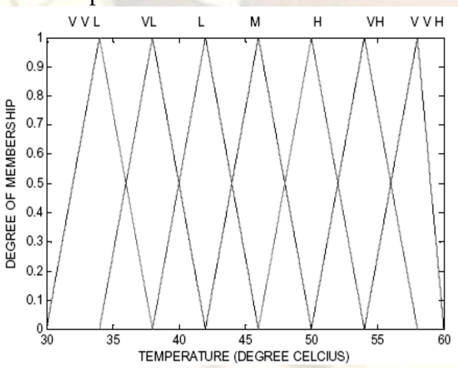

Fig.2: Membership function for temperature

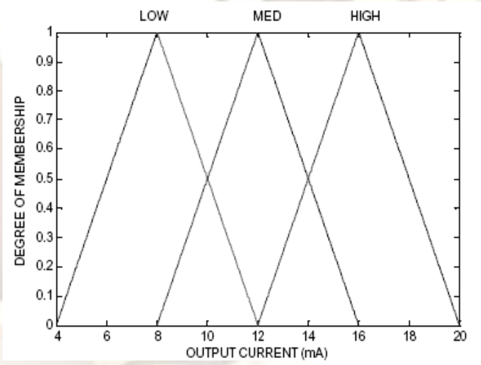

Fig.3: Membership function for output (mA)

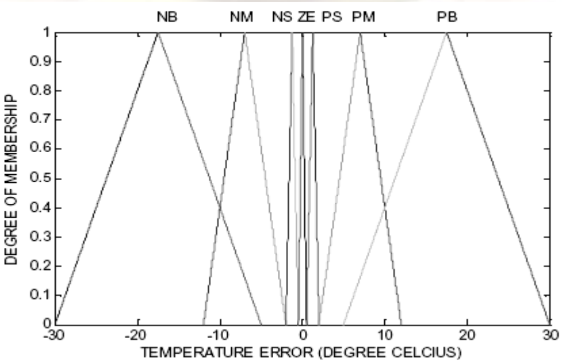

Fig.4: Membership function for error in temperature

TABLE 2: FUZZY ASSOCIATIVE MEMORY FOR FLC

TEMPERATURE / TEMPERATURE ERROR	VVL	VL	L	M	H	VH	VVH
NB	LOW	LOW	LOW	LOW	LOW	LOW	LOW
NM	LOW	LOW	LOW	LOW	LOW	LOW	LOW
NS	LOW	LOW	LOW	LOW	LOW	LOW	LOW
ZE	MED	MED	MED	MED	MED	MED	MED
PS	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
PM	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
PB	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH

Hybrid Fuzzy-PI Controller (PI-FLC)

To overcome the limitations of conventional PI controllers and FLC, a hybrid controller is implemented in which the controller outputs are adjusted based upon the designed fuzzy rules. A gain scheduling technique has been incorporated where the PI controller parameters (K_C and K_i) are tuned in a predefined way. Based on the operating region, fuzzy inference will determine the new values of proportional and integral gain. The basic advantage of this technique results from the enlargement of the operational area of linear controller, thus enhancing its capability to compensate for nonlinearities in the system.

The operational region of heat exchanger (30°C-60°C) is divided into six different zones. The input-output characteristic of each zone is modeled as a first order process with dead time (FOPDT) using step response method [7]. The process parameters for different zones are tabulated in Table 3. The PI controller settings are then determined for each of these zones using Skogestad IMC tuning rule [8] as shown in Table 4.

TABLE 3: ZONE WISE PROCESS PARAMETERS

Region No.	Region (°C)	Process Gain (K_P)	Time Constant (τ (sec))	Dead Time (θ (sec))
I	(36-39)	-0.028	745	98
II	(39-41)	-0.0194	809	49.2
III	(41-43)	-0.0173	716	107.4
IV	(43-46)	-0.0294	539	119
V	(46-48)	-0.024	417	86
VI	(48-52)	-0.0316	405	65.4

TABLE 4: ZONE WISE PI CONTROLLER SETTINGS

Region No.	Region Range (°C)	K_c	T_i
I	(36-39)	-135.75	780
II	(39-41)	-423.8	809
III	(41-43)	-192.68	716
IV	(43-46)	-77.03	539
V	(46-48)	-101.02	417
VI	(48-52)	-97.98	405

The hybrid Fuzzy-PI controller is designed with two input variables, temperature and error in temperature. The universe of discourse for these two inputs are (30°C-60°C) and (-30°C to +30°C) respectively. The membership functions for the two input variables are shown in Fig.5-6 and the FAM used for the control is shown in Table 5.

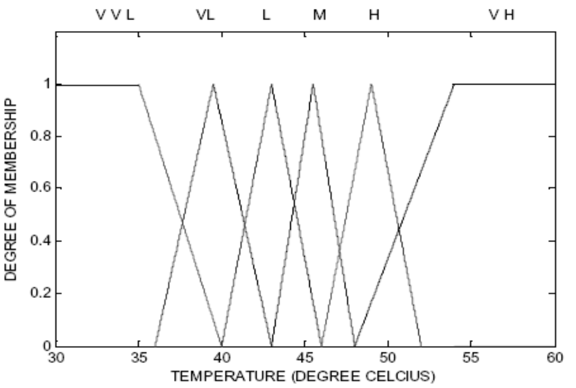

Fig.5: Membership functions for temperature

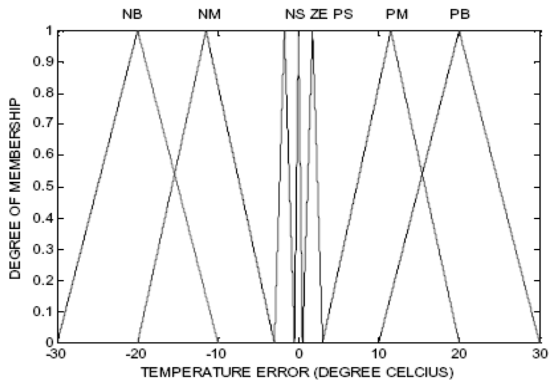

Fig.6: Membership functions for error in temperature

TABLE 5: FUZZY ASSOCIATIVE MEMORY FOR PI-FLC

TEMPERATURE TEMPERATURE ERROR	VVL	VL	L	M	H	VH
NB	LOW	LOW	LOW	LOW	LOW	LOW
NM	LOW	LOW	LOW	LOW	LOW	LOW
NS	PI-I	PI-II	PI-III	PI-IV	PI-V	PI-VI
ZE	MED	MED	MED	MED	MED	MED
PS	PI-I	PI-II	PI-III	PI-IV	PI-V	PI-VI
PM	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
PB	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH

In the regions of temperature error defined by; NM: Negative Medium, NB: Negative Big, PM: Positive Medium, PB: Positive Big and ZE: Zero, the implication scheme used is Min-max and the defuzzification scheme used is Method of heights as mentioned above in the case of designed FLC for faster tracking of the control variable. However, in the regions of NS: Negative Small and PS: Positive Small; the outputs are the values of controller parameters (K_C and K_i) which are then used to estimate the actual controller output as per the standard PI algorithm. The defuzzified controller output is given as:

$$u(t)=K'_c e(t)+K'_i \int_0^t e(t)dt \quad (1)$$

Here the proportional gain K'_c and the integral gain K'_i are modified based upon the fuzzy inference. The value of K'_c and K'_i are estimated as follows [8]:

$$K'_c = \sum_{j=1}^{m} \alpha_j k_{cj} \quad (2)$$

$$K'_i = \sum_{j=1}^{m} \alpha_j k_{ij} \quad (3)$$

Where k_{cj}; is the value of K'_c corresponding to the membership grade α_j for the j_{th} rule and k_{ij} is similarly defined.

Thus the controller settings used to estimate the defuzzified controller output is a weighted combination of the individual controller settings of different regions, the weights being defined by the corresponding membership grades. The basic advantage of this technique results from the enlargement of the operational area of linear controller thus providing effective tracking of control variable.

IV. RESULTS AND DISCUSSION

The effectiveness of the designed FLC and PI-FLC is tested in real time for different setpoint changes. For the readings shown below the hot water flow rate is kept at a constant value of 75 LPH. For servo response the initial setpoints are 39, 42 and 45°C as shown in Fig.7 and 47, 50 and 46 °C as shown in Fig.8 respectively.

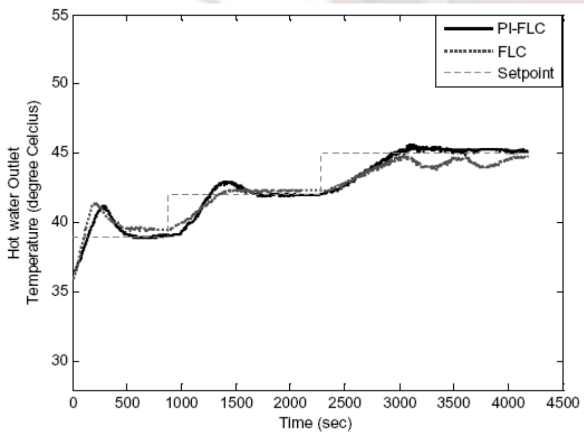

Fig.7: Servo tracking for setpoint changes: (39-42-45)°C

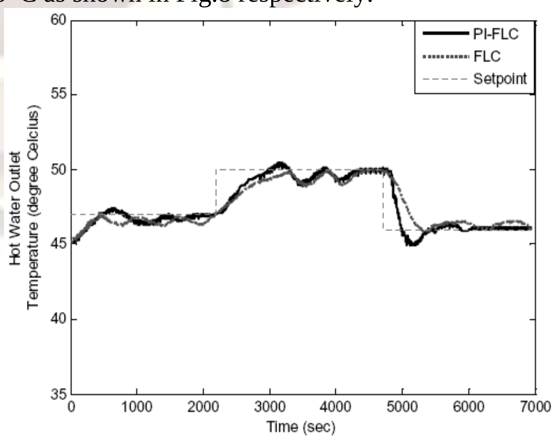

Fig.8: Servo tracking for setpoint changes: (47-50-46)°C

The effectiveness of the controller for disturbance rejection is carried out by introducing a sudden change in the hot fluid flow rate. After the hot water outlet attains the initial setpoint of 43°C, the flowrate of the hot fluid is increased by 50 LPH for two minutes. Similarly for the initial setpoint of 50^{o}C, hot fluid flowrate is increased from 75 LPH to 125 LPH for two minutes. The responses of the system to the introduced disturbances are shown in Figs. 9 and 10.

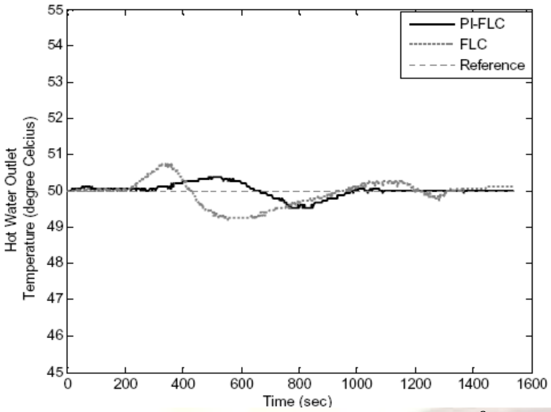

Fig.9 Response for load change at 43^{o}C

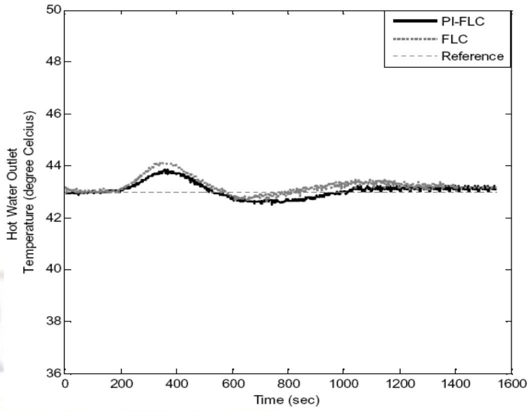

Fig.10 Response for load change at 50^{o}C

It is seen that the PI-FLC controller tracks the setpoint effectively and in lesser time as compared to FLC controller. The FLC controller shows poor performance as the operating condition changes from one setpoint to another. However, the inherent advantages of PI and fuzzy together helps PI-FLC to take appropriate action in case of changes in operating condition. The effectiveness of the proposed controller over FLC is further seen in terms of reduced ISE and IAE error values. The error estimation for the designed controllers for setpoint tracking and load changes are shown inTable6.

TABLE 6: ERROR VALUES FOR PI-FLC AND FLC CONTROLLER

CONTROLLER	FUZZY-PI		FUZZY	
PERFORMANCE CRITERIA	IAE	ISE	IAE	ISE
Servo Change (39-42-45)^{o}C	1102.29	1888.182	1297.11	1920.55
(47-50-46) ^{o}C	1454.24	2333.09	1581.29	2687.04
Load Change 43 ^{o}C	123.59	48.66	158.6	84.87
50 ^{o}C	68.43	19.37	142.74	70.73

V. CONCLUSION

The design of the FLC and a type of hybrid fuzzy-PI controller for a laboratory scaled shell and tube heat exchanger is discussed and the developed algorithm is tested in real time. The results obtained shows that a hybrid controller based on conventional PI and intelligent scheme like fuzzy significantly improves the system performance in terms of settling time. The estimated error values are also less. Thus, the problem of nonlinearity in systems like heat exchangers can be handled using hybrid control methodology effectively.

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