FINAL REPORT OF THE RESEARCH PROJECT 5/98

DEVELOPMENT OF FUZZY LOGIC CONTROLLERS IN MANUFACTURING OF RESIN ADHESIVES FOR WOOD INDUSTRIES

Ramachandran Nagarajan

School of Engineering and Information Technology,
Universiti Malaysia Sabah
Kota Kinabalu

February 2003

ABSTRACT

Controlling of exothermic reaction in manufacturing of resin adhesives is being performed in chemical industries through human reasoning, expertise and interaction . Human interaction has been a source of control errors which affect the quality of resin product. Since the process of manufacturing of resin adhesives involves exothermal reaction, automatic control of temperature is very difficult and needs a constant attention by the operator. The exothermic reaction is nonlinear and un-predictably time varying and hence cannot be modeled. Due to this, a PID control effort is also not suitable. An Artificial Intelligence based control is the only alternative. Since the control law has to be decided amidst unpredictable environment, Fuzzy Logic Control (FLC) can help in making decisions. This is the motivation of this research. A one-step predictor has been designed and included in the FLC loop to compensate the inherent time delay in the process system. The current research substantiates the FLC methodology and proposes further modifications in the fuzzy logic controller in order to overcome some shortfalls of the system such as reduced speed of control and varying steady state errors in temperature responses. The main reason of these shortfalls is due to some un-measurable parameters of the system that vary slowly and unpredictably. An approach of adaptive control is found appropriate in compensating such parameter variations and is applied as an outer loop to the earlier FLC system. Several experiments performed on this system confirm that the new proposal of adaptive predictive fuzzy logic control is effective in overcoming the shortfalls of predictive fuzzy logic control system .

ABSTRAK

Pengawalan reaksi eksotermik dalam pembuatan gam resin di industri kimia dilakukan melalui anggaran, kepakaran dan interaksi manusia. Interaksi manusia telah menjadi punca kepada ralat kawalan yang menentukan kualiti produk resin. Oleh kerana proses pembuatan gam resin mangandungi reaksi eksotermal, kawalan suhu automatik adalah sukar dan ia memerlukan pemerhatian berterusan oleh operator. Reaksi eksotemik adalah tidak linear dan masanya tidak dapat dijangkakan, jadi ia tidak dapat dimodelkan. Oleh kerana itu, usaha mengawal melalui kawalan PID juga tidak sesuai. Kawalan cerdik buatan ('Artificial Intelligence') hanya merupakan satu alternatif. Oleh kerana hukum kawalan perlu ditetapkan dalam suasana yang tidak dapat dijangkakan, kawalan fuzzy logik (FLC) boleh membantu membuat keputusan. Ini adalah motivasi bagi penyelidikan ini. Ramalan satu-langkah telah direka dan dimasukkan dalam gelung FLC bagi mengurangkan ralat masa dalam proses sistem. Penyelidikan ini mengandungi metodologi FLC dan mencadangkan modifikasi selanjutnya untuk kawalan fuzzy logic bagi mengatasi masalah sistem seperti kekurangan laju kawalan dan perubahan ralat keadaan mantap pada respon suhu. Sebab utama bagi masalah tersebut wujud daripada beberapa penbolehubah sistem yang berubah dengan perlahan serta tidak dapat dijangkakan. Satu halatuju menggunakan kawalan adaptif didapati sesuai bagi mewujudkan pampasan untuk perubahan pembolehubah dan telah diaplikasikan pada gelung luaran sistem FLC yang sebelumnya. Beberapa eksperimen yang telah dlakukan pada sistem ini membuktikan bahawa cadangan baru kawalan fuzzy logik jangkaan adaptif adalah efektif untuk menangani masalah sistem kawalan fuzzy logic adaptif.

CONTENTS

=================

RESEARCH REPORT
(Code: 5/98)

DEVELOPMENT OF FUZZY LOGIC CONTROLLER IN MANUFACTURING OF RESIN ADHESIVES FOR WOOD INDUSTRIES

RAMACHANDRAN NAGARAJAN
School of Engineering and Information Technology, UMS

ABSTRACT

Controlling of exothermic reaction in manufacturing of resin adhesives is being performed in chemical industries through human reasoning, expertise and interaction. Human interaction has been a source of control errors which affect the quality of resin product. Since the process of manufacturing of resin adhesives involves exothermal reaction, automatic control of temperature is very difficult and needs a constant attention by the operator. The exothermic reaction is nonlinear and un-predictably time varying and hence cannot be modeled. Due to this, a PID control effort is also not suitable. An Artificial Intelligence based control is the only alternative. Since the control law has to be decided amidst unpredictable environment, Fuzzy Logic Control (FLC) can help in making decisions. This is the motivation of this research. A one-step predictor has been designed and included in the FLC loop to compensate the inherent time delay in the process system. The current research substantiates the FLC methodology and proposes further modifications in the fuzzy logic controller in order to overcome some shortfalls of the system such as reduced speed of control and varying steady state errors in temperature responses. The main reason of these shortfalls is due to some un-measurable parameters of the system that vary slowly and unpredictably. An approach of adaptive control is found appropriate in compensating such parameter variations and is applied as an outer loop to the earlier FLC system. Several experiments performed on this system confirm that the new proposal of adaptive predictive fuzzy logic control is effective in overcoming the shortfalls of predictive fuzzy logic control system.

1.0 INTRODUCTION

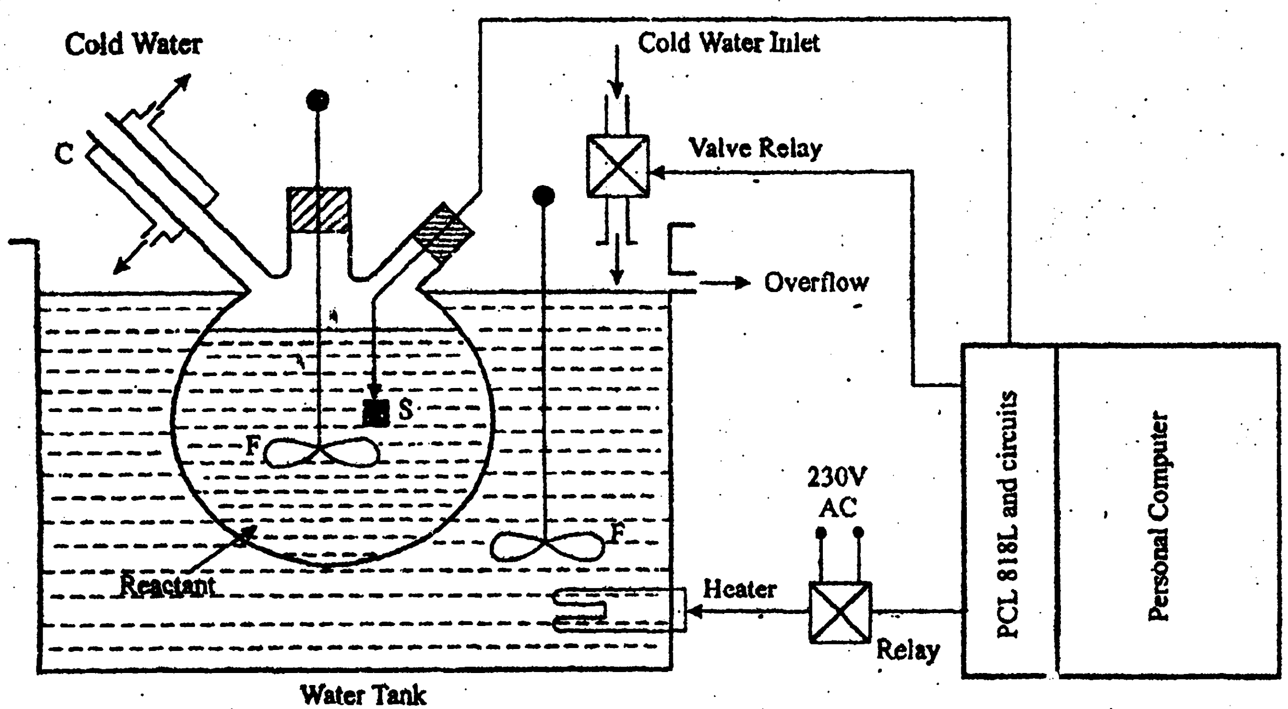
The process of manufacturing Phenol-Formaldehyde resin adhesive is through exothermic reactions and demands a precise control of temperature against rapid variations of internally produced heat within the reactants mixture. The process is to follow a required temperature profile which has a constant rate of increasing temperature for a selected period and regulation of temperature at a specified level for another selected period. The quantity of deviation between the ideal temperature profile and that of the actual determines the quality of resin adhesive. Modeling of the exothermic process for exercising any model-based control (such as PID control) is very complex and is not practicable. Any modeling inaccuracy results in imprecise control that leads to irreversible solidification of the resin mixture. The resin manufacturing process requires an accurate follow-up of the specific profiles of temperature variations. This follow-up has been found very difficult. The reasons include unpredictable values of transport delay, un-measurable system parameters, fluctuations in heat loss, changes in tank water quantity and the variations in viscosity of the reactant. Hence Intelligent Control methods are the only suitable solution. Fuzzy Logic Control (FLC) methodology is one among them (Jamshidi, Vadiee, and Ross, 1993). FLC can be used in this type of un-predictable (or Fuzzy) environment for tracking and regulating temperature profiles required by the resin manufacturing process. An important advantage of applying FLC is that it does not require a mathematical model and the control is based on human heuristic decisions. Such a model free control design is not only suitable in this research but also useful wherever such a fuzzy environment occurs.

FLC was first introduced in 1970s as an attempt to control systems that are structurally difficult to model due to inherent non-linearities and due to inaccurate understanding of process behaviour (Zadeh, 1965). Since then, FLC has been employed in several process control applications. A proportional-Integral Control (PI) based on Fuzzy logic principles has been successfully implemented in many applications such as controlling temperature and pressure of steam engines (Zadeh, 1973). FLC was employed in controlling the steering and speed of automobile engines (King and Mamdani, 1977), in process control of cement kiln (Oustergaad, 1977), manipulating pH values in mineral processing (Kelly and Spottishwood, 1982), gelatinisation of starch and denaturing proteins in extrusion cooking process (Eerikainem et al; 1986) and in several areas of automatic processes control (Sugeno, 1985)

In this research of controlling an exothermal process for manufacturing resin adhesives, a laboratory based reaction pilot process system and the required computer interface circuits have been constructed and a FLC software has been developed and tested for its suitability in controlling the temperature of the resin mixture along a given temperature profile. Initially, the process is tested with a newly designed Predictive Fuzzy Logic Control in producing resin adhesives. Then the process control is enhanced to Adaptive Predictive fuzzy logic to compensate un-measurable and unknown variations of parameters in several locations of process system. A variety of experiments have been performed to test the performance of the process with Adaptive Predictive Fuzzy Logic Control. All experiments reveal that the proposed control using Adaptive Fuzzy Logic Principles is very well suited in the control of exothermal process systems.

2.0 THE PROCESS CONROL SYSTEM

The block schematic of the Personal Computer (PC) based reaction system designed for investigating the effect of FLC on process temperature is represented in Fig 1. The reaction system consists of a water tank and a round bottom flask fitted with a condenser. The flask is immersed in tank water and a set of heaters with sufficient heating capacity are inserted in the bottom of the tank. The tank is also provided with an inlet through which cold water could flow in and an outlet to drain away the overflowing water. Two relays are included -



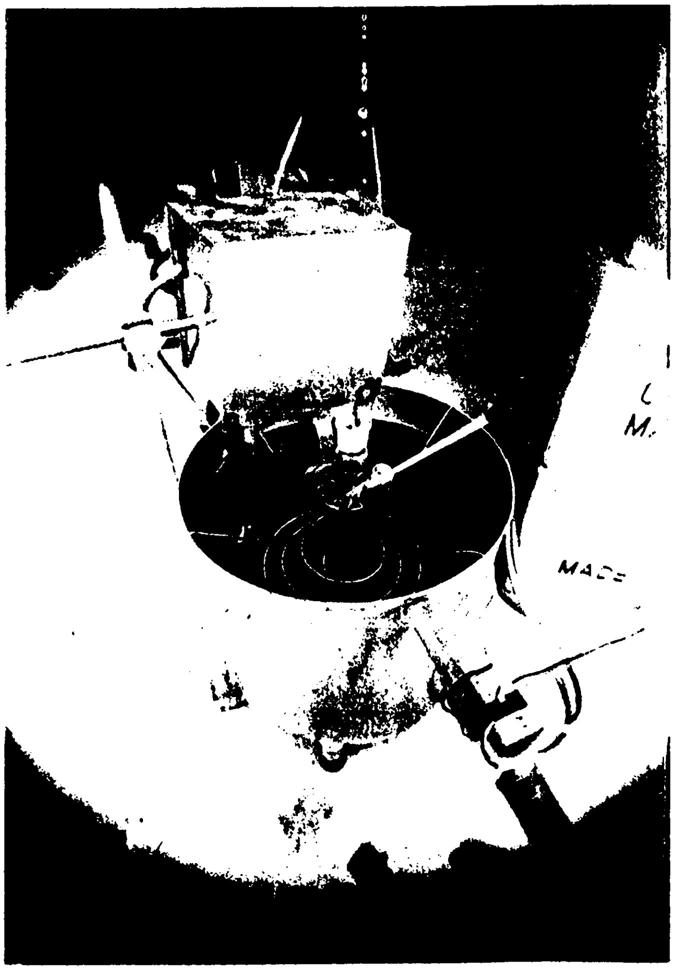
S : Sensor, F : Stirrer; C : Condenser

Figure 1 Schematic Diagram of the PC based Reaction System one for controlling the flow of cold water in to the tank and the other for controlling the heater supply. Phenol and Formaldehyde, in required proportions, are mixed in the flask using an in-built motorised stirrer. The temperature of the mixture (reactant) in the flask is thus controlled by ON-OFF duration of heater current and that of cold water in flow. A temperature sensor (LM35) is employed for the measurement of the reactant temperature. The sensor and the relays are connected to the PC through suitable interface circuits. A FLC software has been developed and refined so that the temperature of the reactant follows the given temperature profile as closely as possible. Since, the developed thermal process system is basically a time delayed system with an average delay of 20 s, a first order real time prediction has been included in the software thus making the system controlled by a predictive FLC. The constructed process system and its components are shown in Fig 2.

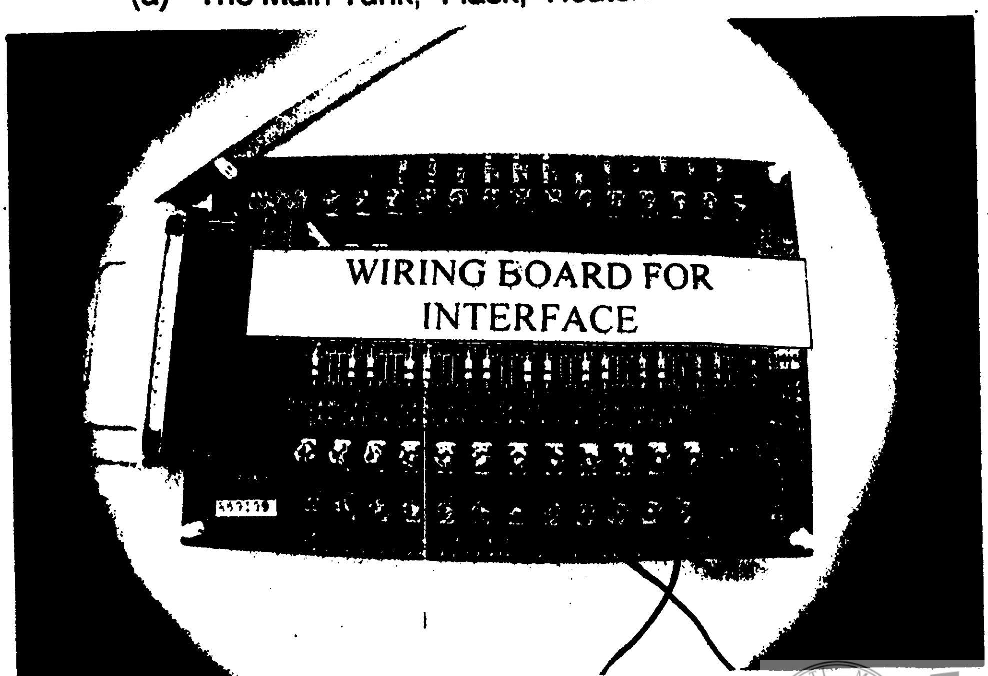
The interface hardware consists of a PCL 818 data acquisition (DA Card) for PC, an input circuit and an output circuit. The PC is IBM compatible Intel 486 based and the DA card is installed in the parallel bus of the PC.

An IC temperature sensor LM 35 is employed for the measurement of reactant temperature. LM 35 is a three terminal device and can measure temperature from 0 to 100 degree C.

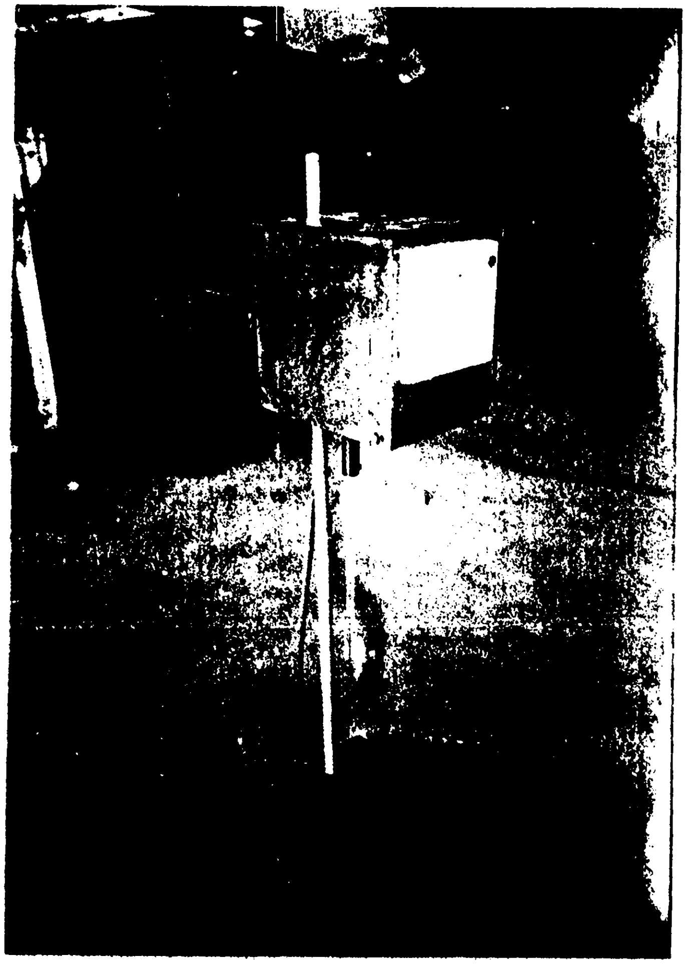
The output circuit controls the duration of heater current and cold water valve through their respective ON/OFF relays. The control circuit to the relays are of discrete voltage levels (0 V or 5 V) and are generated by the DA card through its control software. The required input to heater (230 V AC) and to the valve solenoid are switched ON or OFF by relay contacts at appropriate time and duration as decided by Fully Logic Conroller.



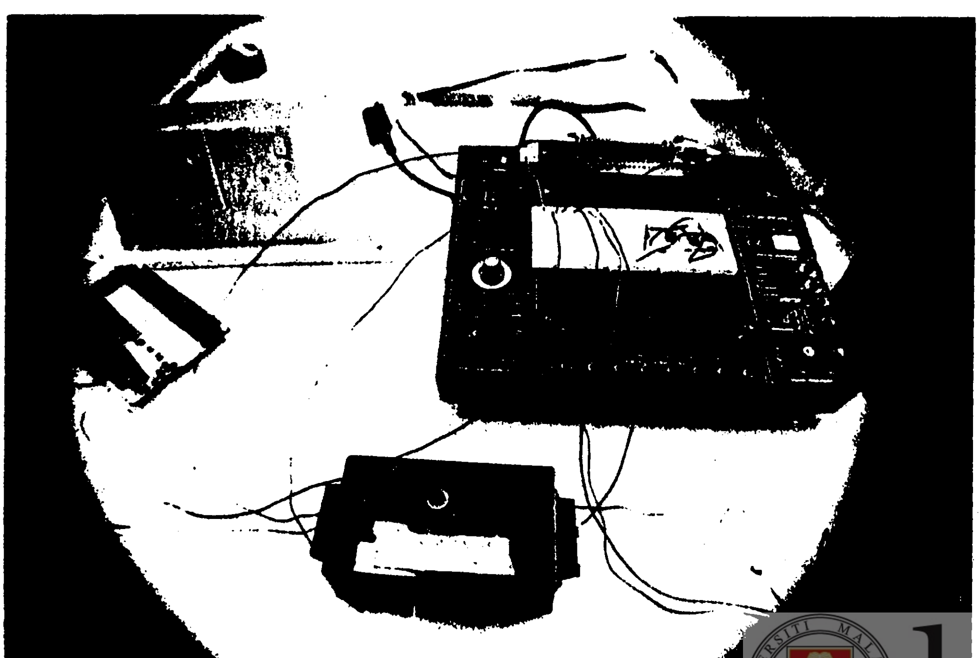
(a) The Main Tank, Flask, Heaters and Stirrer



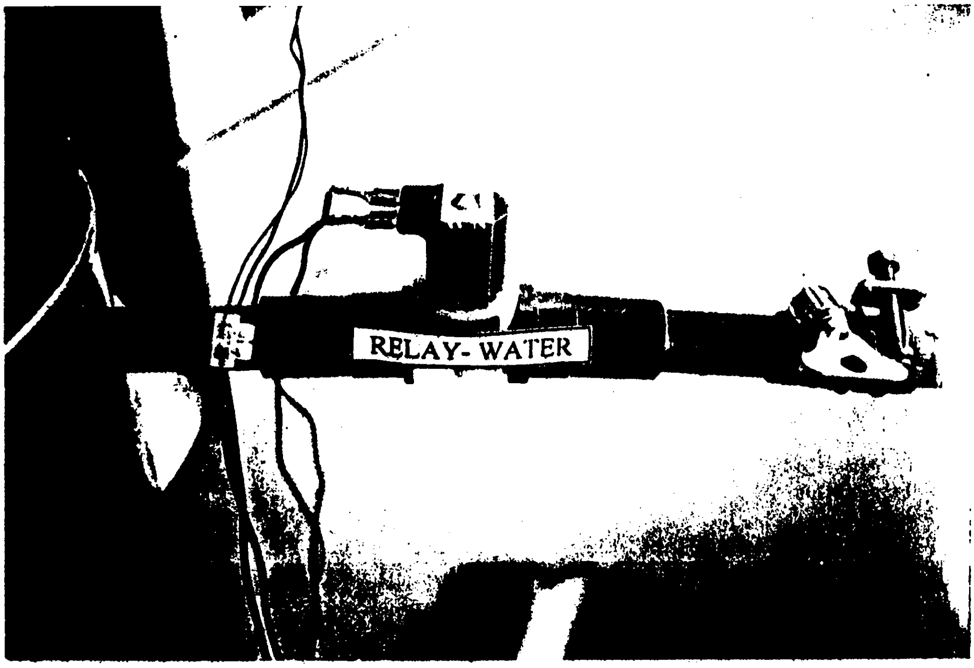
(b) Wiring Board for Interface, flat cable to PC.



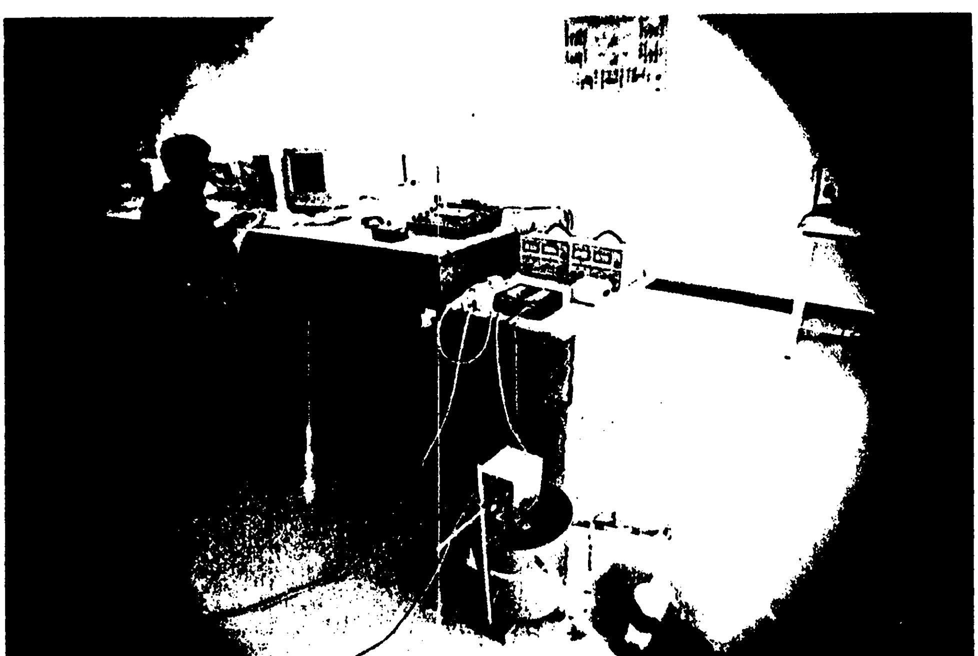
(c) The Stirrer and its Controller



(d) The Interface Electronics for Relay Control



(e) The Relay for Water Inlet and its wiring to PC



(f) The Complete Experimental Set-up

Figure 2 The Constructed PC Based Reaction System

3.0 THE PREDICTIVE FLC

A one-step ahead predictor was designed to compute the values of temperature errors at the next sampling instant from the current and past sampled data of the measured temperature of the reactant. The control is then derived from FLC rules via human reasoning. A new form of linear prediction algorithm (Nagarajan and Kumar, 1998) computes the predicted value of temperature error, Ep(k+1), and the predicted value of change in temperature error, ΔEp(k+1), in °C, where k is the current sampling instant. The average sampling duration, after performing several experimentations, has been measured as 20 sec.

The block diagram of the predictive FLC system is given in Fig 3. The block representing the predictor has one input, E(k), ie. the difference between the measured temperature T(k) and the reference temperature T*(k), at instant k, and two outputs Ep(k+1) and ΔEp(k+1). The FLC algorithm computes the duration of the heater input (H sec) or the duration of cold water inflow (V sec) that is to be implemented within the sampling duration of 20 sec. The tank-flask system responds to these inputs and produces a temperature T(k+1) at the next the sampling instant.

The working ranges of each input and output of the FLC are decided from a set of experiments as

Ep(k) = -2°C to +2°C ΔEp(k) = -2°C to + 2°C (1)

H(k) = 0 to 20 sec and V(k) = 0 to 20 sec (2)

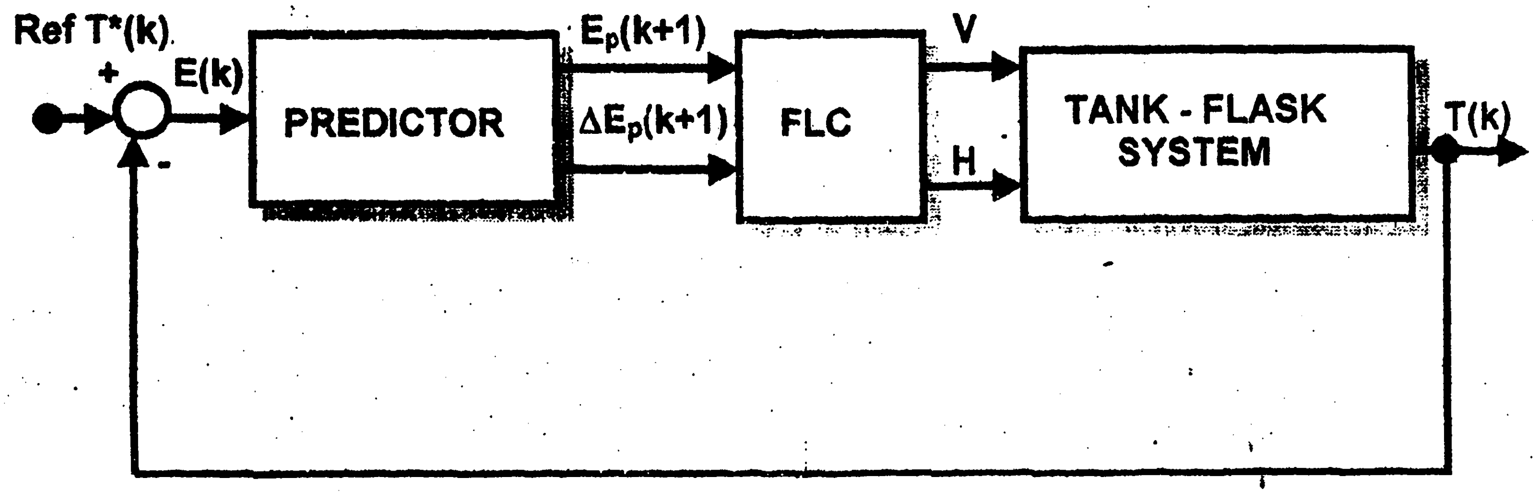


Figure 3 Block Diagram of the Predictive FLC System

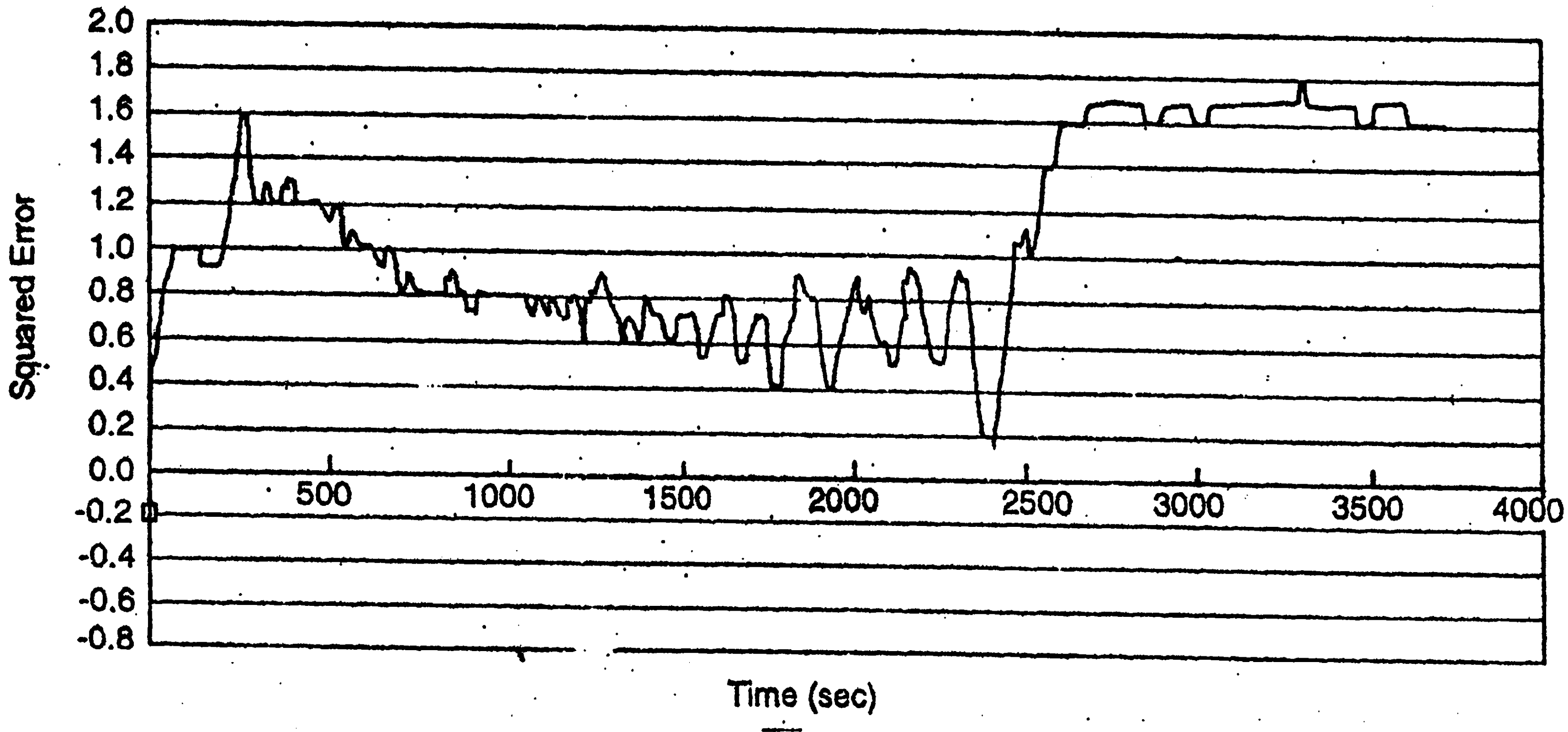


Figure 4. Time Response of Squared Error of Predictive FLC system

temperature, the expected reactant temperature profile and the response of tank water temperature are similar to those presented in a few undergraduate project reports (eg Tee Chin Siong, 2001) and are not given here again since they consists of several temperature responses. In addition we are more interested in responses of temperature errors rather than the temperature responses themselves.

Fig 4 depicts the time response of squared error, $[\ E(k)\ ]^2 = [\ T^*(k)-T(k)\ ]^2$, as obtained in one set of typical experiments. The response shows an appreciable value in steady state error. This indicates that the predictive FLC system does not always offer an assured thermal response with zero steady state error and, hence, needs a modified control methodology in order to improve its steady state performance. This problem may be solved by modifying the FLC rules and / or modifying shape of membership functions. It is the authors' experience that these approaches, if applied to exothermic processes such as the one we discuss here, do not satisfactorily provide real time compensation for the effect of variations of un-modeled process parameters on the process performance, especially the steady state error. Hence, a methodology referred as gain adaptation is introduced in this work in order to minimise the steady state error and to improve the speed of temperature response.

4.0 GAIN ADAPTATION

Compensating the variations of unknown parameters has been a challenging problem in real time control applications. Parameter compensation in fuzzy logic controlled systems has been attempted through several approaches. Recent approaches such as gain adaptation (Kumar and Nagarajan, 2000), gain scheduling (Ling and Edger, 1992) and parameter tuning (Mareels and Polderman, 1996) have been adopted successfully in several FLC systems including process control. In this research, a form of gain adaptation that is based on a recent work in the field of Model Reference Adaptive Control (MRAC) is recommended for compensating the variations of un-modeled parameters. The MRAC is characterised by high speed adaptation and has been accepted as one of the best approaches for parameter compensation when the unknown parameter variations are slow (Astrom and Wittenmark, 1995). In addition, the speed of parameter compensation increases when the number of gains to be adapted is smaller. The un-modeled parameters do vary slowly and their effect can be efficiently compensated by MRAC while the predictive FLC can compensate for rapid exothermic reactions within the phenol-formaldehyde mixture. However, a successful and asymptotically stable MRAC requires to satisfy a necessary condition that the forcing functions are sufficiently rich (Wong, 1994). That is, the forcing functions are to have sufficient number of frequency components in order to excite all modes of the process dynamics in assuring a perfect parameter adaptation. A successful adaptive scheme for a n-order dynamical system, for example, requires at least 2n frequency components in the forcing function. This is also validated in our proposal as we consider, in the following, a first order model which has several frequency components in its forcing function. Thus, the introduction of an adaptive control loop in the already designed FLC system for compensating the variations of un-modeled parameters in the process system is found appropriate.

4.1 The Error Model

The adaptive form of predictive FLC system is given in Fig 5 . Two gains q(k) and f(k) are placed respectively in the forward path and in the feedback path of the

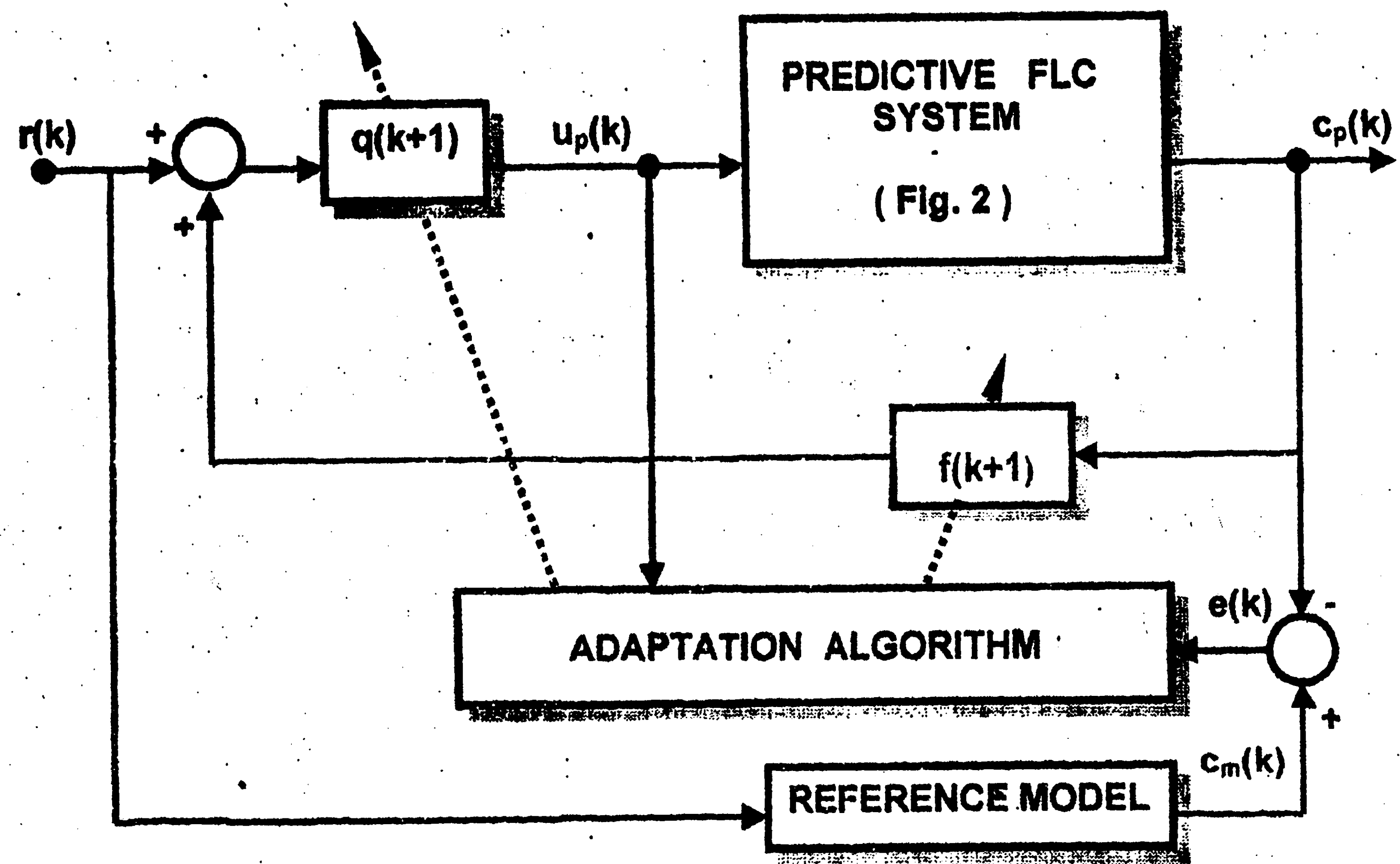


Figure 5 The Adaptive Form of Predictive FLC System

The required FLC algorithm is developed from the knowledge base of people operating the system and is incorporated through membership functions of input and output signals. Several distribution of membership functions are possible for a successful control action (Jamshidi, Vediee and Ross, 1993). One set of membership functions and the corresponding rule base have been decided from the acquired knowledge through a series of experiments. The structure of a new set of membership functions and the Fuzzy Associative Memory (FAM) are given in Fig 6 and in Table 1 respectively. As examples, two of the 49 rules of Table 1, one for deciding the duration of heating and the other for deciding the duration of cold water in flow, are interpreted as :

$$\text{IF } E = NS \text{ AND } CE = PM, \text{ THEN } H = PS \tag{3}$$

$$\text{IF } E = PS \text{ AND } CE = NB, \text{ THEN } V = NM \tag{4}$$

where H and V are mutually exclusive. $E = Ep(k+1)$ and $CE = \Delta Ep(k+1)$. Max-Min inference with centroid defuzzification (Jamshidi, Vediee and Ross, 1993) is adopted in determining the crisp values for V or H.

The methodology of predictive FLC is described as: At instant k, T(k) is measured. The predictor computes the values of predicted errors E and CE from T(k) and T(k-1). FLC decides the values of V (or H) and implements between the instant k and instant (k+1). The system responds to the control and T(k+1) is measured at instant (k+1). The measurement and control thus continue till the predicted errors vanish and remain at zero.

Several experiments were conducted to evaluate the performance of this predictive FLC system. The performance of the system is acceptable in spite of unpredictable exothermic reactions except frequent occurring of steady state errors in the responses. In some responses the process takes unduly long time to reach the specified final temperature. The responses of the measured reactant

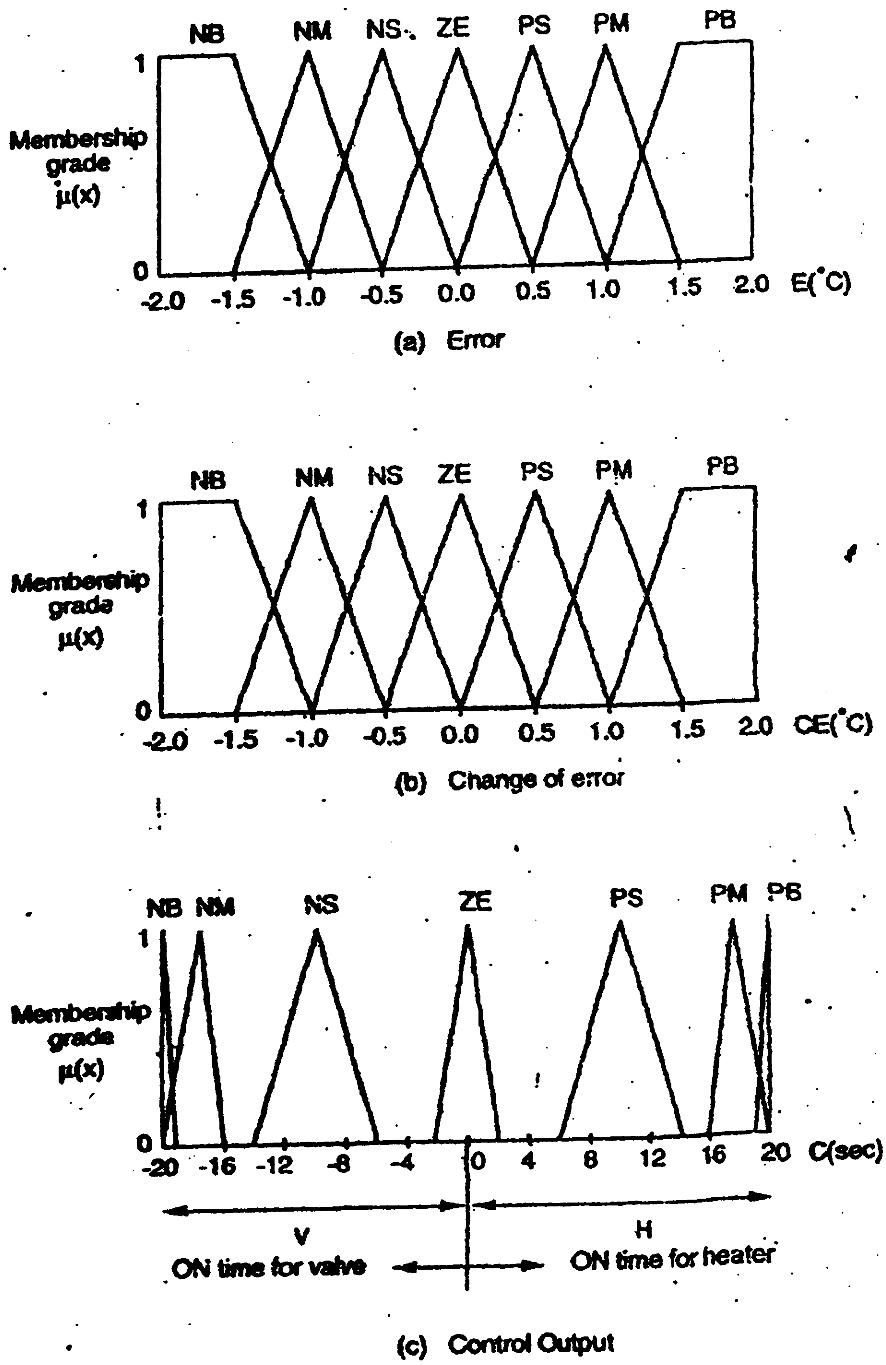


Figure 6 The Structure of the New Set of Membership Function

Table 1: FAM RULES

CHANGE OF ERROR (CE)	ERROR (E) NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

NB: Negative Big; NM: Negative Medium; NS: Negative Small; ZE: Zero:
PS: Positive Small; PM: Positive Medium; PB: Positive Big.

system. These gains are adjusted on-line through an adaptation algorithm in such a way to cancel the effect of slowly varying parameters on system performance. The adaptation algorithm and the gains are outside the existing predictive FLC structure so that any involved modifications in software and hardware of the already designed process control are avoided.

While the predictor tries to compensate the inherent delay of the tank-flask system, the predictive FLC makes the process system to follow the required temperature profile against the fast exothermic reactions. However, the steady state performance of the process is affected by the slowly varying un-modeled parameters. Observation through various responses of reactant temperature reveals that the process behaves like a first order dynamic system. This enables one to describe the process dynamics through the difference equation

$$c_p(k+1) = a_p\, c_p(k) + b_p\, q(k+1)\, [\, r(k) + f(k+1)\, c_p(k)\,] \tag{5}$$

where a_p and b_p are two process system parameters that are varying slowly about their respective unknown mean values in an un-predictive manner. r(k) is a reference signal derived from the given temperature profile and the process output $c_p(k) = T(k)$, the temperature of the mixture. The adaptive mechanism has to continuously modify the gains q(k) and f(k) in such a way that the process system behaves like a reference model, the dynamics of which is known and is given by

$$c_m(k+1) = a_m\, c_m(k) + b_m\, r(k) \tag{6}$$

wherein $c_m(k)$ is the model output; a_m and b_m are fixed model parameters and their values are chosen for any desired stable response which the process system is expected to acquire.

Define the adaptive system error as

$$e(k) = c_m(k) - c_p(k) \tag{7}$$

Then, the error response is derived from Equations (5) to (7) as

$$e(k+1) = a_m\, e(k) + [\, a_m - a_p - b_p\, q(k+1)\, f(k+1)\,]\, c_p(k) + [b_m - b_p\, q(k+1)\,]\, r(k) \tag{8}$$

A successful adaptation algorithm continually forces $q(k) \rightarrow q^*$ and $f(k) \rightarrow f^*$ where q^* and f^* are the ultimate but unknown average values of gains. Then, from Equation (8),

$$b_m = b_p\, q^* \tag{9}$$

$$a_m = a_p + b_m f^* \tag{10}$$

are satisfied at ultimate gain values and $e(k) \rightarrow 0$ making the reference model and the process system to have the same dynamics.

4.2 Stability of Error System

The stability of error system, Equation (8), and hence the stability of overall adaptive predictive FLC process system, is ensured when the adaptation algorithm leads $q(k)$ and $f(k)$ towards their respective ultimate values and also drives $e(k)$ towards zero simultaneously. This is ensured through the following analysis:

Adding and subtracting a term ($b_m\, f(k+1)\, c_p(k)$) to Equation (8) and using Equations (9) and (10), another form of error dynamics is derived as

$$e(k+1) = a_m\, e(k) + b_m\, \theta^T(k+1)\, z(k) \qquad (11)$$

where the signal vector z(k) and the parameter error vector θ(k) are denoted respectively by

$$z^T(k) = [\, c_p(k) \quad u_p(k) \,] \qquad (12)$$

$$\theta^T(k) = [\, \alpha(k) \quad \beta(k) \,] \qquad (13)$$

wherein,

$$\alpha(k) = (\, f^* - f(k) \,), \quad \text{and} \quad \beta(k) = (\, 1/q(k) - 1/q^* \,) \qquad (14)$$

are the scalar parameter errors. $u_p(k) = q(k+1)\,[\, r(k) + f(k+1)\, c_p(k) \,]$ is the forcing function of the predictive FLC system (Fig 5). It is assumed, without the loss of generality, that the scalar gain q(k) and q^* are of same sign and $q(k) \neq 0$, at any k.

Let the parameter errors be continuously modified by the algorithm

$$\alpha(k+1) = \alpha(k) - \mu(k)\, c_p(k-1) \qquad (15)$$

$$\beta(k+1) = \beta(k) - \mu(k)\, u_p(k-1) \qquad (16)$$

where μ(k) is a time varying factor to be determined. This factor takes the responsibility to force α (k) and β (k) towards zero which then drives e(k) to zero simultaneously.

From Equations (15) and (16), the parameter error dynamics is written as