CHAPTER 1

INTRODUCTION

1.1 GENERAL CONCEPTS

A Continuous Stirred Tank Reactor (CSTR) is one of the most important unit operations in chemical industries and it exhibits highly nonlinear behaviour and usually has wide operating ranges. Chemical reactions in a reactor are either exothermic or endothermic and therefore require that energy either to be removed or added to the reactor to maintain constant temperature. Most of the reactors dealt in the literature for control purposes have been modeled as ideal CSTRs.

In an ideal CSTR, it is assumed that the reactor is well-mixed, meaning that the concentration at different positions of the CSTR is identical throughout the reactor. On the contrary, the mixing in the nonideal CSTR is not uniform, resulting in bypass and stagnant regions (dead space). Due to bypass, the flow passing through the reactor will be less than the total volumetric flow rate and as a result, there will be slower decay of the transients in the concentration response in the reactor than in the case of perfect operation. In the dead space where the fluid does not enter, there results a lesser reactor volume than in the case of perfect operation. Hence, the fluid will pass through the reactor more quickly and as a result the transients in the concentration in the reactor will decay more rapidly than in the case for the perfect operation.
Further, the majority of chemical reactors are naturally nonlinear and Multi-Input Multi-Output (MIMO) systems. Compared with single-input single-output (SISO) counterparts, MIMO systems are more difficult to control due to the existence of interactions among input and output variables. Although considerable effort has been dedicated to this problem and many design techniques have been proposed over the decades, control system design and implementation for MIMO processes are still a big challenge for practical control engineers.

The interactive multivariable systems can be controlled by the following approaches:

a. A multivariable or centralized MIMO controller or by
b. A set of SISO decentralized controllers.

Algebraic decoupling methods or optimal multivariable control techniques are usually applied to obtain centralized MIMO controllers. While centralized multivariable controllers are complex, the decentralized control system enjoys certain advantages:

a. It requires fewer parameters to tune
b. Loop failure tolerance of the resulting control system can be assured during the design phase.

Therefore, the decentralized control methods are more often used in process control applications. The primary task in the design of decentralized control system is to determine the loop configuration. Since, the pioneering work of Bristol (1966), the Relative Gain Array (RGA) based techniques for control loop configuration have been widely used in industries including blending, energy conservation and distillation columns. The most important
advantage of RGA based technique is its simple calculation since only process steady state gains are involved.

It is well known that the industrial reactors are nonlinear. However, such systems can be approximated by a linear model in the neighbourhood of the operation point, provided the neighbourhood is small enough or there are only small system uncertainties. If the operating space is large or the degree of nonlinearity is severe, then it is intuitive to expect that a single linear model may not be accurate to approximate the nonlinear system satisfactorily. Moreover, it is quite common for the chemical plants to produce more than one type of product, the choice of the product being dictated by market forces. As a result, transition between different points occur, which necessitates the use of a controller or control structure that can successfully regulate the plant not only at the particular initial and final operating points, but also in the entire transition regions. In order to control such a highly nonlinear system, gain scheduling approach has been widely used. In the conventional gain scheduling approach the nonlinear system is linearized at several equilibrium operating points and the local linear controllers are designed at each of these points. The linear controller gains are then interpolated or scheduled between the selected equilibrium points to obtain a global nonlinear controller. There is a vast amount of approaches to gain scheduling. Many of them are application specific. In the following sub-section, the classical and Fuzzy approaches are discussed.

1.1.1 Classical Gain Scheduling

The classical approach to gain scheduling consists of four steps as follows:

a. Approximate the nonlinear system locally using standard linearization about a set of equilibrium points.
b. Perform controller synthesis for the local models such that a family of linear controllers is obtained.

c. Formulate the nonlinear controller by either interpolating the gains of the local controllers or by switching between the linear controllers.

d. Implement the nonlinear controller to verify whether it provides satisfactory results.

The limitation of the classical gain scheduling technique is that it exploits the behaviour of the system only in the vicinity of the equilibrium operating points (this generally imposes an inherent slow variation requirement on the system to ensure that the state remain close to the equilibrium which is additional to any slow variation requirement associated with the change in linearized dynamics as the system moves from the vicinity of one equilibrium point to another). However, in order to meet increasingly stringent performance objectives, gain scheduled controllers are frequently required to operate both during transitions between equilibrium operating points (which might transiently take the system far from equilibrium) and during sustained operations far from the equilibrium. A number of approaches developed in the fuzzy logic and neural network literatures attempt to relax restrictions to near equilibrium operation while remaining closely related to the classical gain scheduling philosophy.

1.1.2 Fuzzy Gain Scheduling

Fuzzy gain scheduling is a special form of model-based fuzzy control that uses linguistic rule fuzzy reasoning to determine the controller parameter transition policy for a dynamic plant subject to large changes in the operating state. The main advantage in using fuzzy logic to adapt the PID parameters is that switching between operating conditions is smoothly carried
out, since the controller parameters are adjusted via a bump less transfer algorithm.

With the advances in digital technology, the science of automatic control now offers a wide spectrum of choices for control schemes such as adaptive control, neural control and fuzzy control. However, more than 90% of industrial controllers are still implemented based on PID algorithms, as no other controllers can match their simplicity, clear functionality, applicability and ease of use. In the proposed work, a trade-off is obtained by enhancing the tuning and the gain scheduling capabilities of PID controllers with the help of soft computing techniques namely, the genetic algorithm and the fuzzy logic.

The following section presents the literature review pertaining to the modeling and control of the nonideal CSTR addressed in the proposed work.

1.2 LITERATURE REVIEW

Nonlinear behaviour of the chemical process is not an uncommon characteristic. This feature not only heightens the control problem but also necessitates a nonlinear dynamic model of the process for control studies. Most of the control theory deals with the design of linear controllers with linear systems. PID controllers are proved to be perfect controllers for simple and linear processes. These controllers have been installed at most process plants, since they are simple, robust and familiar to the field operator. Nikolaou et al (2001) presented the developments and further directions on linear control of non-linear processes and summarized that virtually all chemical processes are non-linear, but for many of them, linear controllers are adequate. Nahas et al (1992) have proposed the use of internal model control
using neural network for the control of chemical process. Since, it is difficult to describe the complete system behaviour using a single linear model; the performance of the control schemes based on single linear model being used to control the nonlinear process cannot yield satisfactory performance. Many different approaches have been proposed for using local models to approximate nonlinear systems (Johansen and Murray-Smith 1997). The multiple linear model based controller design has attracted the process control community and a plethora of multiple model adaptive control schemes has been proposed in the control literature (Gundala et al 2000, Yu et al 1992, Dougherty and Cooper 2003). A supervisory control method was proposed by Morse (1996, 1997) and Hespanha et al (2001). In Banerjee et al (1997), the multiple local models are combined into a single parameter varying global model. It is assumed that each model has a controller that has been designed to perform satisfactorily within its operation region but not necessarily during a transition. The design of multivariable controllers using decoupled control scheme for a multi-input multi-output process is presented by Astrom et al (2001). Detuning method for decentralized control is explained by Lee et al (2002). The pairing criteria for decentralized control of unstable plants are proposed by Sigurd Skogestad et al (1993). The widely used pairing criteria involving the Nieldderlinksi index and the steady state Relative Gain Array (RGA) used for evaluating the integrity under decentralized control are extended to open loop unstable plants. Qiang Xiong et al (2006) have analyzed a dynamic loop pairing criteria for decentralized control of multivariable process utilizing both the steady state gain and bandwidth information of the process.

With the development of the Artificial Intelligence (AI), optimally tuned PID controllers have been developed using evolutionary techniques, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO) technique and Differential Evolution (DE) methods. Genetic algorithm based
Optimization is a powerful tool for the design of controllers (Herrero et al (2002), Liu Fan Er Meng Joo (2009)). Oliveira et al (1991) used a standard GA to determine initial estimates for a variety of classes of Linear Time-Invariant (LTI) systems, encompassing minimum phase, non-minimum phase, and unstable systems. A comparison between the optimization based PID tuning using GA and PSO is described by Chao Ou et al (2006). Yeo et al (2006) have proposed a tuning method for PID controllers based on the closed loop identification and GA and apply it to control the chemical process. A Colonial Competitive Algorithm (CCA) based optimization of the coefficients of the decentralized controller for a MIMO evaporator system was proposed by Rajabioun et al (2008). The authors claim the superiority of the CCA to the Ziegler-Nichols and Genetic Algorithm tuning techniques for the decentralized PID controllers. Design of Evolutionary algorithm based PID controllers is discussed by Iruthayarajan et al (2009); the authors have performed simulation studies to develop decoupled multivariable PI and PID controllers for a binary distillation column plant using evolutionary algorithm.

In the last two decades, significant developments have been made in the field of nonlinear process control. Closed system performance of a nonlinear system is degraded when the operating conditions change and a linear controller may not track the changes in the operating states. Two important approaches to the design of control structures for nonlinear systems are exact feedback linearization which is based on differential geometric control theory given by Klatt and Engell (1998) and gain scheduling techniques based on approximate linearization families as proposed by Xu et al (1994). In order to accommodate the entire operating region of the CSTR, a fuzzy gain scheduled control scheme is an approach. This method involves the determination of controller parameters for each region and requires a scheduler. Jaya et al (2007) proposed fuzzy gain-scheduler assuring smooth transitions for a level process.
Zhao et al (1993), Viljamaa et al (1995), Huang et al (2009) have described the development of a fuzzy gain scheduling scheme of PID controllers for process control. Ruiyao Gao et al (2002) have proposed a nonlinear PID controller used for CSTR using local model networks. They have used operating regime recognition algorithm to obtain the operating regions of the process and then linear models are identified for each region. From the bank of linear models, the authors select the appropriate controller model for the dynamic matrix controller using the switching algorithm. Rezeka et al (2010) have developed fuzzy gain scheduled controllers for a stepper motor. It was shown that fuzzy PID controller provides better performance than conventional PID controller.

Blanchett et al (2000) have developed a simple, yet robust and stable alternative to PID gain scheduling using fuzzy logic. The method is demonstrated with a physical model where PID control performance is improved to levels comparable to Model Predictive Control (MPC).

Among the various reactors, continuous flow stirred tank reactors have been used extensively to study the dynamic behaviour of nonlinear chemical systems. However, these systems have been based on the ideal mixing in the reactor. Balakotaiah et al (1983) have used the singularity theory to construct various bifurcation diagrams describing the influence of changes in the residence time on the temperature in a CSTR in which several reactions occur simultaneously. Lo and Cholette (1983) investigated the multiplicity of conversion in a cascade of imperfectly mixing CSTRs. Liou and Chien (1991) have analyzed the phenomenon of input multiplicity under the conditions of nonideal mixing of Cholette’s model for an isothermal CSTR. The results show that a fraction of the feed does not enter the space of perfect mixing. Liou and Chien (1995) carried out studies on macro mixing and micro mixing effect on the steady state multiplicity in the CSTR.
Chidambaram et al (1996) have proposed a nonlinear integral controller for an isothermal CSTR with nonideal mixing. Padma Sree et al (2003) have proposed a simple method to design PI controllers for an isothermal CSTR with nonideal mixing.

1.3 OBJECTIVES OF THE PRESENT WORK

From the literature review cited, it is observed that the modeling and control of an ideal reactor has been extensively studied and not much of research work is dedicated for the control of a CSTR with nonideal behaviour such as dead space and bypass. Hence, the objective of the present work is to formulate a mathematical model for a nonideal CSTR and investigate a suitable control strategy for the proposed system.

In this research work the specific objectives are as follows:

a. To represent a nonlinear MIMO CSTR as a family of local linear transfer function models at each operating point.

b. To develop the multivariable controllers (using decentralized and decoupled control schemes) for each local model.

c. To develop a global multivariable controller by combining the multivariable controllers at the local models (using gain scheduling technique).

d. To carry out extensive closed loop simulation studies on the CSTR process for both ideal and nonideal cases.
The scope of the present research work is presented in Figure 1.1.

![Diagram](image)

**Figure 1.1 Scope of the present work**

The various topics dealt in the present work are discussed in the following sections.

1.4 MODELING AND CONTROL

A model is a representation of a physical process. Mathematical models of chemical processes are especially useful for the design of new processes, optimization of the existing processes and control of the processes. Models enable prediction about how a process will change when perturbed or modified. There are many types of models that can be developed for a process among which, the first principles model uses the understanding of fundamental phenomena to create a model relationship.
The first principles model of an ideal CSTR with an irreversible, exothermic reaction considered for the simulation study has the following assumptions:

1. Perfect mixing in the reactor and jacket,
2. Constant volume reactor and jacket and
3. Constant parameter values.

The plant inputs are the feed flow \( q \) and the coolant flow \( q_c \). The outputs considered are the effluent concentration \( C_A \) and the reactor temperature \( T \).

The linearized models of the CSTR are obtained in the chosen three different operating points for the ideal CSTR. Nonideal mixing due to the presence of bypass and dead space are considered and the mathematical model is derived for the nonideal CSTR.

The following section presents the procedure for obtaining the conventional controllers for the ideal CSTR using decentralized and decoupling control schemes.

### 1.5 CONVENTIONAL CONTROL

The industrial reactor is naturally a MIMO system. Compared to single input single-output (SISO) counterparts, MIMO systems are more difficult to control due to the existence of interactions between input and output variables. Decentralized control is used for multivariable processes when the interactions in the process are insignificant. Every input-output pair is tuned and controlled using unit controllers separately from other pairs. If the interactions are significant, the structure of the controller has to be
multivariable (centralized control). The size of the interactions in the multivariable process is measured using RGA matrix.

1.5.1 Decentralized Control

In this section, it is proposed to design a decentralized controller for an ideal CSTR. In order to design the decentralized controller, the appropriate pairings among inputs and outputs are chosen using RGA to identify the input-output pairs which will result in reduced interaction. In the present work, it is found from RGA values, $\lambda_{11}$ is negative at all operating points. Since loops should not be formed with negative relative gains, $y_1$ (effluent concentration) should be paired with $u_2$ (coolant flow rate) and $y_2$ (reactor temperature) should be paired with $u_1$ (feed flow rate). The diagonal elements of the decentralized controller are designed using IMC based tuning method. The robustness of the controller depends on the filter parameter which has to be obtained by trial and error method.

In the present work, decentralized control scheme is applied for the multivariable control of an ideal CSTR and the performances are evaluated for set point tracking and load disturbance rejection.

1.5.2 Decoupling Control

When the interactions are strong, multivariable control of CSTR turns out to be complex. Such interactions can give rise to extremely complicated dynamics when the loops are closed and a multi-loop control is inadequate leading to poor performance.

In the present work, the decouplers are designed using static decoupling method to reduce the interaction brought by cross coupling. It consists of two steps: first to design the decouplers and second to design the controllers for the decoupled systems. In the presence of decouplers, the
multivariable system behaves like two independent loops, for which the
collectors can be designed independently. The controllers for the decoupled
system are obtained using IMC based PID tuning method. The robustness of
the controller depends on the filter parameter which has to be obtained by trial
and error method.

1.5.3 Gain Scheduler Design

In the present work, the linear controllers are scheduled using a
gain scheduler which acts like a switch between the operating points, forcing
new controller parameters as it detects the modifications in the set point. This
implies that the gain scheduler together with linear controllers handles
nonlinearity. One drawback of conventional gain scheduling is that the
controller parameter changes may be rather abrupt across boundaries of the
process operating regions, which may result in unsatisfactory or even unstable
control performance. The closed loop simulation studies show that the
performance of the gain scheduled decoupling control using IMC based PI
controller is better than that of gain scheduled decentralized control using
IMC based PI controller.

In the following section an attempt is made to improve the
performance of the controllers using soft computing techniques such as
 genetic algorithm and fuzzy logic.

1.6 CONTROLLER DESIGN BASED ON SOFT COMPUTING
TECHNIQUES

In the proposed work, the performance of the reactor is improved
by utilizing optimal controller settings obtained using GA. The GA based PI
implements the characteristics of global optimization to optimize the PI’s
control parameters: $K_C$ and $K_I$ to provide control effect for the individual
linear regions. The objective function for tuning the controller is the minimization of the Integral Square Error. In order to cover the entire operating range, an attempt has been made in this work, to use fuzzy gain scheduler for allocating the appropriate controller parameters.

In the present work, the performance of the CSTR using fuzzy gain scheduled GA tuned multivariable controllers is analysed using decentralized control and decoupling control schemes. From the studies carried out, it seen that decoupling control scheme provides better results than the decentralized control scheme for the multivariable control of the ideal CSTR.

1.7 MULTIVARIABLE CONTROL OF NONIDEAL CSTR

The multivariable controllers designed for the ideal CSTR do not provide satisfactory results when the nonideal mixing due to dead space and bypass are considered. Hence, an attempt is made to design controllers considering the nonideal behaviour of the CSTR. Accordingly, the controllers are designed by incorporating the dead space and bypass dynamics of CSTR. The procedure for designing the controllers as given in sections 1.5 and 1.6 are repeated for designing the controllers for this nonideal CSTR.

Thus, the major findings of the present work include the following:

a) Fuzzy gain scheduled GA based control of the CSTR provides better results as compared to the conventional control scheme

b) The closed loop performance of the real CSTR is improved by incorporating the effects due to the dead space and bypass.
1.8 ORGANIZATION OF THE THESIS

Accordingly, the thesis consists of six chapters. Chapter 1 deals with the need for the present work, organization of the thesis along with the related literature survey. The mathematical modeling of an exothermic CSTR (ideal and nonideal cases) is presented in Chapter 2. The design of multivariable controllers using conventional techniques for the ideal CSTR with two inputs and two outputs is presented in Chapter 3. The design of multivariable controllers for the ideal CSTR with two inputs and two outputs using soft computing techniques is dealt with in Chapter 4. The effect of nonideal mixing and the effectiveness of the proposed control schemes using soft computing techniques on the nonideal CSTR are dealt with in Chapter 5. The summary, conclusions and suggestions for future work are presented in Chapter 6.