CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION TO THE PROBLEM

Drying is one of the essential operations followed in chemical, metallurgical, pharmaceutical and food process industries. It helps to remove moisture content from the material to be dried by applying heat through conduction, convection or radiation. Different types of dryers used in various process industries include tray, rotary, spray and fluidized bed dryers (FBDs). The FBDs are more advantageous over other drying methods as they ensure thorough mixing and rapid rates of heat and mass transfer between hot fluid and particles (Mujumdar 1986). Air Heating System (AHS) is an important component of convective-type of dryers. These dryers transfer the heat to the wet material by convection through the heating medium namely air. In the AHS, heater voltage is manipulated to control exit air temperature, which is then sent to drying chamber. The exit air temperature depends on inlet air properties like: humidity, temperature, velocity and residence-time inside the heating chamber (Panda and Rao 1991). Manual control of drying process experiences considerable difficulties due to the following aspects:

(i) non-uniform properties of inlet air
(ii) difficulty in continuous measurement of moisture content of the inlet air
(iii) parametric non-linearity
(iv) non-minimum phase behaviour and
(v) process dead-time.
In the AHS, the control objective is to maintain the exit-air temperature at the desired set value. The schematic diagram of computer controlled drying system is shown in Figure 1.1. The automatic control schemes of air heating systems for industrial applications are mostly based on empirical relationships and classical control methods. Due to lack of proper modelling techniques, the controller performance is not satisfactory. Hence, it is felt that there is a need to design and synthesise appropriate control strategies and implement them using the state-of-the-art computer control facilities.

Last decade has seen the rapid development and expansion in the control technology, methodology and strategy. A higher level of automation can be achieved by incorporating fault diagnosis, condition monitoring, supervision and training along with tuning and adaptation. The greater the ability of the controller to efficiently cope with the process complexity and uncertainty, the more intelligent the controller is. In other words, the ability of a system to sense the environment and adapt the non-linear behaviour (adaptation), process the information depending on the load/set-point changes (learning) and generate and execute control (decision making for action) constitute an Intelligent Control System (ICS). The controllers based on fuzzy logic and neural network come under the category of ICS (Swain and Subudhi 1996).

1.2 STATE OF THE ART AND MOTIVATION FOR THE PRESENT RESEARCH WORK

This section reviews the developments in the various control strategies used for the drying systems. All landmark papers are systematically classified in chronological order, in the six distinct categories; namely, conventional feedback controllers, model based controllers using conventional methods, ANN based MPC schemes, fuzzy logic controllers, GA based fuzzy logic controllers and neuro-fuzzy
Figure 1.1 Schematic of computer controlled drying system.
controllers for drying process. The problems and issues of the various schemes presented in the land mark papers are discussed.

1.2.1 Conventional Controllers

Automatic control of AHS is necessary for obtaining the desired product quality. Air-temperature controllers are designed and implemented on chemical or food drying units and are reviewed as follows: Myron et al (1973) controlled the product temperature and drying quality in a food processing plant by manipulating the feed rate. Harbert (1974) discussed automatic control of the dryer by moisture measurement and manipulation by the temperature difference method. In this method, at the start of the drying cycle, the feed (pharmaceutical powder) temperature is kept at the wet bulb temperature of the incoming air. The temperature of the product was measured by a thermocouple and its value was stored. When the product temperature increases, it is compared with the previously stored value. When the temperature difference reaches 15°C, a signal automatically switches the dryer off. It is reported that the moisture content deviation of the product is within 1% from the desired value. Ostapchuk et al (1975) presented a method of controlling the temperature of the drying agent, treating the heat consumed as the performance criteria. Palancz (1975) presented methods for optimum control of drying processes. Fink and Schelling (1977) proposed a digital control system using a process computer. With the aim of minimising the heat requirement, Baumshtein et al (1979) demonstrated an optimum control policy of multizone convective dryers using correlated function and lagrangian multiplication technique. Philips et al (1988b) developed control strategies for the start up of fluidized sand bath. A self tuning PID controller was used in this approach for conventional dual-mode temperature control and was tested experimentally. Tiwari et al (1994) evaluated the drying time for wheat crop for a given moisture content. Nelson and Gardner (1996) presented a scheme for optimising the control performance of paper machine dryer by developing a tuning strategy, minimising the non-linearities inherently present in the process.
1.2.2 Model Based Controllers

The papers cited in the section 1.2.1, presented control algorithms that do not incorporate the model of the plant into the basic control structure. Hence these control schemes are insufficient to compensate for parameter variation and can not adapt to changes in the process environment, whereas, model based control schemes can provide the advantage of robustness in control. Garcia et al (1989) presented a number of design techniques emanating from model predictive control (MPC) techniques namely Dynamic Matrix Control (DMC), Model Algorithmic Control (MAC) and Internal Model Control (IMC). MPC techniques are very attractive tools for addressing the difficulties arising from model uncertainty. They also meet the requirement to satisfy dynamically a number of constraints on states and inputs. Here tuning is direct and the constraints are considered explicitly in the algorithm. Cutler and Ramarkar (1980) outlined the DMC scheme which minimises an objective function to find out future moves of the manipulated variable subject to predetermined error tolerance. The error is computed as the sum of the squares of the differences between the predicted outputs from the plant model and from the desired output variable trajectory over a prediction horizon. The control move thus computed is implemented. The difference between process output and predicted model output is used for correcting the model mismatch and unmeasured disturbance. Garcia and Morari (1982a, 1985b, 1985c) presented a review of control concepts, design procedure and tuning guidelines of IMC schemes. Their study infers that the IMC can handle constraints and incorporate dead time compensation. Panda and Rao (1994) derived DMC and IMC algorithms for a continuous FBD. They implemented both the schemes on an actual pilot plant of the dryer. The DMC scheme showed good set point tracking in the presence of measurement noise. Farkas and Rendik (1996) presented the advantages of using a block-oriented system simulation based on a physical model to simulate the drying process of different agricultural materials, instead of using uncertain empirical equations. Nishizawa et al (1994) presented a control system for a rotary dryer considering large load disturbances. Instead of controlling the entire temperature profile, this system requires only two...
measurements. They are the material temperature at the exit of the dryer and the
temperature at which the drying mechanism changes from constant rate of drying to
falling rate of drying. The multivariable MPC scheme presented by Nishizawa et al,
showed superior performance when integrated with the soft sensor compared to
conventional multi loop PID control system. Mehra et al (1995) presented an MPC
technique to obtain optimal temperature and pressure profiles in a hot isostatic
pressing furnace which minimises the ultimate cost per unit of production. In this
technique Risk Sensitive Optimal (RSO) Control was used in combination with MPC
to increase robustness and to improve steady state regulation. Further, the response
time and attenuation of low frequency disturbance are found to be better in the MPC
RSO scheme.

1.2.3 ANN based MPC schemes

The drying process is highly complex, non-linear and dynamic in nature.
Hence developing a realistic model representing the entire dynamics of the system
becomes a difficult task. Models already available make assumptions of varied
nature. Inaccuracy in the modelling due to various assumptions yields degraded
performance of controllers. The non-linear MPC can be used for non-linear complex
processes. But they have the following disadvantages (Wayne Bequette 1991).

(i) There is no guarantee of convergence or vigorous proofs of robustness
with respect to stability and performance.
(ii) Computational time could be an issue with complex models that have
relatively fast dynamics.
(iii) Determination of the initial conditions for the state variables in the
prediction horizon optimisation is difficult.
(iv) Development of a non-linear model for a non-linear model based control
strategy is a cumbersome process.
The most expensive part of the realisation of non-linear predictive control scheme is the derivation of a mathematical model. In many cases, it is even impossible to obtain a suitable process model because of the complexity of the process and/or lack of knowledge of the critical parameters of the models like temperature dependent mass transfer coefficients, viscosities etc., (Draeger et al 1995). A promising way to overcome these problems is to use Artificial Neural Network (ANN) as non-linear black-box model for representing the dynamic behaviour of the process (Fukuda and Shibata 1992).

The use of ANNs in control systems can be seen as a new step in the model based control of drying process. Works on ANNs though have a long history of 40 years, there is a recent resurgence in this field caused by new network topologies and algorithms (Lipmann 1987). The ANNs try to mimic the biological brain neural networks into mathematical models. Multi Layer Perceptron (MLP) has arisen as the most popular choice due to its broad modelling capabilities (Hunt et al 1992). The invention of the Back Propagation Algorithm (BPA) has played a major role in the resurgence of interest in artificial neural networks. BPA is a systematic method for training multilayer ANNs (both feedforward and feedback network). The advent of ANNs have inspired new resources for the possible implementation of better and more efficient control.

Tan (1993) presented a real-time temperature control using an adaptive neural control scheme. The control architecture of the scheme includes an adaptive neural model which is used for identification and control. The learning strategy for on-line training of the neural controller is described in detail in this paper. Spieker et al (1993) presented dynamic models for several thermal processes using feedforward neural networks. The synthesis of ANN is directly associated with the minimisation of an objective function, normally defined as the square of the difference between the output of the process being modelled and the output predicted by the network. The identified inverse neural model of the plant is used as a controller in one of the controllers presented. Hepworth et al (1994) described a hybrid neural control
scheme for heater battery. The hybrid controller uses an ANN which learns the non-
linear static characteristics of the plant, to generate feedforward control action. The
unmeasured disturbances are dealt with a conventional controller which acts as a feedback trimmer. This work infers that hybrid control scheme produces more consistent control and is less sensitive to variations in the temperature of water supplied by the boiler. Nault and Maltain (1996) monitored the machine performance in a paper factory with on-line dryer expert system, using 120 inputs through an existing data acquisition system, expecting the machine to travel along a well defined highway stacked-out by a series of proven benchmarks. The dryer expert system is located in the operator room and generates information through diagnosis to help the operator to bring back the operating conditions to normal. Topalov et al (1996) presented a fast on-line learning method for ANN structures by using GA and dynamic BPA jointly for coarse and fine tuning of weights. It is shown through simulation and real-time temperature control of oven that this learning algorithm has faster convergence ability and better performance in reducing mapping error during on-line learning of ANNs. This leads to an improvement of the transient response of adaptive neuro systems. The method proposed in this paper can be applied to many practical areas such as system modelling and control. Rogers and Dagli (1996) presented an ANN based wood dryer control scheme at the dehydration stage of wood waste pyrolysis. Standard BPA network structure is used in this approach to associate patterns of sensor readings with appropriate heuristically determined control responses. Kaminski et al (1996) aimed at applying ANNs for modelling the dynamics of thermal degradation process. In this work a feedforward ANN was trained with experimental data gathered from vбро-fluidized bed dryer. It was shown that a small-size network is capable of predicting the quality index in a limited range of drying process parameters. Temeng et al (1995) showed that the ANN model based controller could achieve tighter temperature control for disturbance rejection in the industrial packed bed reactor, compared to a conventional control scheme. Here, a multi-pass packed bed reactor temperature profile was modelled via recurrent neural network using BPA-through-time training algorithm. This model was then used in conjunction with an optimizer to build a non-linear MPC.
Thus, ANNs can be used as a non-linear black-box model representing the dynamic behaviour of the non-linear process. Because of their massive parallel architecture, they can perform computation at much higher speed. In addition, ANNs have many interesting features like learning and self-organising capabilities which make them adapt to changes in process variables. Due to the presence of semi-linear sigmoidal functions in the hidden neurons, the model developed using ANN describes the non-linear dynamics of the process over the whole operating range. This makes the tuning of corresponding controller less cumbersome. However, the success of ANN technique depends upon the judicious choice of ANN architecture and learning parameters. Also, unlike FLC scheme ANN does not possess the decision making capability based on linguistic rules.

1.2.4 Fuzzy Logic controllers

Fuzzy logic is a branch of mathematics that allows a computer to model the real world the same way that people do (Zadeh 1965). FLC has become an active area of research for industrial processes which are not amenable to conventional control, especially where there is a lack of quantitative data regarding the input-output relations. It attempts to emulate human mind for monitoring the process parameters and to take decisions regarding the control action. Fuzzy logic converts a linguistic control strategy, based on expert knowledge into an automatic control strategy. Some of the advantages of FLC are listed below (Cox 1992):

(i) Qualitative linguistic rules are used to provide deterministic control.
(ii) The rules are not specific to a given model.
(iii) Detailed mathematical models are not necessary
(iv) Ideal for complex or non-linear systems.
(v) Compatible with existing control solution
(vi) Provides robust control and hence is insensitive to the influence
of environmental fluctuations.

(vii) Demonstrates smooth action even with a small number of rules.
(viii) Hardware implementation is possible.

More details about FLC are presented in Lee (1990a and b) and Mendel (1995). Since its introduction fuzzy logic has been used successfully in a number of control applications. The first application of fuzzy set theory to the control of dynamic processes was reported by Mamdani and Assilian (1975). The control problem was to regulate the engine speed and the boiler pressure of a small laboratory scale model of a steam engine and boiler combination. Despite of the non-linearity, noise and the strong coupling in the plant, they obtained acceptable control using fuzzy logic controller.

Kickert and Lemke (1976) examined the performance of fuzzy control algorithm for an experimental warm water plant. Here, the problem was to regulate the temperature of water, leaving a tank at a constant flow rate by altering the flow of hot water in a heat exchanger in the tank. A secondary control task was to ensure a fast response to step changes in outlet water temperature set-point. Tong et al (1980) examined the behaviour of an experimental FLC algorithm on an activated sludge waste water treatment process. They concluded that a fuzzy algorithm, based on practical experience, can be made to work on this difficult process. Yamazaki and Sugeno (1985) presented a microprocessor based FLC scheme for industrial processes. The other applications of FLC scheme namely; coal fired kiln (Larsen 1979), water quality control (Yagishita et al 1985), automatic train operation systems (Yasunobu et al 1986), elevator control (Fugites 1988), nuclear reactor control (Bernard 1988) biological muscle relaxant anaesthesia control (Linkens et al 1991) and heat exchanger (Ostergaard 1997) are presented by Srinagesh (1994). The various areas of applications have pointed out the effectiveness of fuzzy control schemes in controlling complex ill-defined processes that could otherwise be controlled only by skilled human operators. The interest in applying fuzzy control scheme has been growing rapidly in recent years. Bremner and Postlethwaite (1994)
investigated the control of moisture in the outlet product from a dryer using relational fuzzy model-based control system. The dryer is used to process the material left over from whisky distillation plant into animal feed. Murphy et al (1996) compared the performance of fuzzy supervised internal model control with conventional IMC structure. The fuzzy supervisor was implemented on an actual paper machine to show the improved controller performance when the operating point is varied.

From the above survey it is clear that it is possible to have the controllers, based on the fuzzy logic approach, with some modifications and extensions to the available controllers, in order to achieve better performance.

So for, the membership functions required for the FLC design are generated either iteratively, by trial-and-error or by human experts. Procyk and Mamdani (1979) introduced a linguistic self organising FLC (SOFLC) which uses an iterative procedure for altering membership functions to improve the performance of an FLC. But it is heuristic and still subjective. Shao et al, 1988 has reported real time implementation of SOFLC scheme for motor speed control and temperature control of a heater. They reported that the scheme could cope up with large time lag and non-linearity. Graham and Newell (1989) has reported a fuzzy model based adaptive control of a simulated first order liquid level process with varying gain and time constant.

1.2.5 Genetic Algorithm based Fuzzy Logic Controllers

Holland (1992) first proposed Genetic Algorithm (GA). Further research in GAs were carried out by Grefenstette (1986), Goldberg (1989). In the recent research, the application of Genetic Algorithm (GA) has been shown as a promising tool for the design of control schemes. The trail-and-error method of generating membership functions in a conventional FLC scheme takes considerable on-line time. A task such as generation of optimal membership functions is a natural candidate for Genetic Algorithm (GA), to make the controller to perform optimally.
Srinivas and Patnaik (1994) presented a survey on genetic algorithms. Filho and Treleaven (1994) presented a review which classifies genetic algorithm environments into application-oriented systems, algorithm-oriented systems and toolkits. They also presented detailed case studies of leading environments. Kristinsson and Dumont (1992) applied GA for system identification and control. Karr (1991) used GA to generate membership function for a cart-pole problem. The task for the controller was as follows: A wheeled cart has a rigid pole, hinged to its top. The cart is free to move right or left along a straight bounded track and the pole is free to move within the vertical plane parallel to the track. The cart is to be kept within the predefined limits of the track and the pole should be prevented from falling beyond a predefined vertical angle by applying a force of fixed magnitude to the left or right of the base of the cart. The objective is to bring the cart to rest: at the centre of the track with the pole balanced. GA was applied for a pH control process to generate optimal membership function (Karr and Gentry 1993). Homaifar and McCormick (1995) examined the applicability of GA to solve the cart-centring problem. Kim et al (1995) designed fuzzy controller using GA.

1.2.6 Neuro-Fuzzy control

In recent years, research on fuzzy systems and neural networks has received considerable attention and obtained many successful applications in a wide variety of areas. Fuzzy systems have demonstrated to be well suited for dealing with ill-defined and uncertain systems. ANN on the other hand, are well known for their learning capabilities. Combination of the fuzzy logic with ANN is then able to enhance the capability of intelligent systems to learn from experience and adapt to changes in an environment with qualitative imprecise, uncertain or incomplete information.

Some ways to exploit the complementary relationship between fuzzy logic and ANN presented by Loos (1994) are listed below.
(i) Neural networks may be trained to generate membership values for a fuzzy logic membership function.

(ii) Fuzzy logic function may be used to fine-tune a neural network training algorithm.

(iii) The inputs can be filtered through a fuzzy function before entering a neural network.

(iv) The outputs can be filtered through a fuzzy function after being processed by network.

(v) Fuzzy logic functions may access data stored within neural network-based memories.

(vi) Fuzzy conditional statements may be used to activate subsets of a neural network based system and vice-versa.

The computational process for fuzzy-neural systems are presented in Gupta and Rao (1994). The advanced techniques and fundamentals in neuro-fuzzy synergisms for modelling and control are reviewed by Jang and Sun (1995). Recently the resurgence of interest in the field of ANNs has injected a new driving force into the "fuzzy" literature. The BPA which drew little attention till its applications to ANN, is actually an universal learning paradigm for any deterministic or fuzzy models. As a result, a fuzzy inference system can now not only take linguistic information (linguistic rules) from human experts, but also adapt itself using numerical data (input/output pairs) to achieve better performance. This gives fuzzy inference systems an edge over ANN, which cannot take linguistic information directly. They presented design methods and the advantages of Adaptive-Network based Fuzzy Inference System (ANFIS), for modelling and control applications. Horikawa et al (1992) presented a fuzzy modelling method using fuzzy neural networks with the BPA. The proposed method identifies the fuzzy model of a non-linear system automatically. The feasibility of the method was examined using simple numerical data. Lin and Cunningham (1995) developed simple and effective fuzzy neural models for complex systems from a knowledge of the input and output data. They introduced the concept of fuzzy curve and used it to identify the input
variables to estimate the number of rules needed by the model and set the initial weights for the fuzzy-neural network model. This method quickly identifies the significant input variables. Since the initial structure and weights of the ANN are properly set, only a few training iterations were needed for ANN to converge. The final fuzzy memberships were used to simplify the fuzzy-neural model. The fuzzy-neural models built by them were of simple structure, taking less training time. Khalid et al (1994) proposed an adaptive fuzzy-neural control system for a water batch process, by integrating two neural models with a basic FLC. One ANN model is used as plant emulator and the other as a compensator for basic FLC to improve its performance on-line. The function of the plant emulator is to provide the correct error signal at the output of neuro-fuzzy compensator without the need for any mathematical modelling of the plant. Results show that the adaptive fuzzy-neural control performance is superior when compared to poorly tuned FLC and conventional digital PI controller under identical conditions of varying complexities in the process. Khalid and Omatu (1995) presented temperature regulation of water bath system using FLC. They compared the performance of FLC with neuro-control algorithm, generalised predictive control scheme and PI control scheme. They found that the computation time using the FLC is less as it mainly involves logic operations and comparison. Liu and Yan (1997) proposed a Fuzzy Logic Based Neural Network (FLBN) to develop a case based system for diagnosing symptoms in electronic systems. They also demonstrated that the FLBN was able to perform fuzzy AND/OR logic rules and to learn from samples, through data obtained from a real call-log database. They also showed that FNN can learn from previous cases to generate the domain knowledge and to reject noise present in the data.

The survey of current research work reveals the growing interest in the application of ANN, FLC and GA in modelling and control of various industrial applications. ANN can be used as a non-linear black-box model, representing the dynamic behaviour of the process. The model, thus formulated can be used to synthesise model based controllers. FLC can also be successfully implemented for the drying process. GA can be used as an effective tool for obtaining optimal
membership function in the design of membership functions of FLC. ANN can be used to carry out fuzzification of FLC scheme. The hybridisation techniques namely, fuzzy logic with neural and GA technique, presented, provide directions for pursuing further research for the implementation of appropriate control strategies.

1.3 SCOPE OF THE THESIS

In the light of above discussion, the present work aims at alleviating the difficulties in the conventional schemes by designing intelligent control strategies namely, ANN based MPC, FLC, GA based FLC and NFC schemes for the exit-air temperature control of AHS (Figure 1.2). The difficulties encountered in developing an accurate realistic model for AHS to synthesise conventional MPC scheme are overcome by using ANN model of the plant in the controller design. An experimental set-up of AHS is fabricated for determining the model parameters using the experimental results obtained. These model parameters are used to synthesise various control schemes. The performance of these control schemes are investigated further through simulation and evaluated using error integral criteria. The closed loop experimental studies were also carried out by implementing an intelligent control scheme (FLC) on the fabricated experimental set-up.

1.4 ORGANISATION OF THE THESIS

Chapter 2 deals with the details of the fabricated experimental set-up of AHS interfaced through signal conditioning module and thyristor based control module to the computer with the help of a high performance AD/DA cards. The open loop studies, formulation of mathematical model incorporating various dynamics including voltage and speed variation and identification of plant parameters are discussed. Developing ANN model of AHS using BPA with momentum factor and learning rate (using experimental data obtained from openloop study) is also presented.
Figure 1.2 Scope of the present investigation.
The details of closed loop simulation studies carried out using conventional control schemes namely PI, PID and MPC are presented in chapter 3. The performance of the three schemes for set-point tracking is presented. The comparison of time domain specifications of the three controller schemes developed and their evaluation using performance indices are also presented.

Chapter 4 presents the details of closed loop simulation studies carried out using intelligent control schemes namely, ANN based MPC, FLC, GA based FLC and NFC schemes. The ANN based MPC scheme is synthesised using the mathematical model of the process (obtained from the open loop studies) in parallel with the process plant represented by the formulated ANN model. The knowledge of designed optimal PID controller is used to develop the FLC scheme. The advantages of finding the optimal membership values of the FLC scheme using GA is discussed. Also, the merits of carrying out scale mapping with the help of ANNs to transfer the two fuzzy input variables into the universe of discourse is highlighted. The closed loop behaviour of ANN based MPC scheme, FLC scheme, GA based FLC scheme and NFC scheme for set-point tracking (of exit-air temperature) is studied and presented. The comparison of time domain specifications of the four intelligent controller schemes developed and their evaluation using performance indices are also presented.

In chapter 5, the details of implementation of an intelligent control scheme (FLC) on the experimental set-up are presented. The hardware details of the computer controlled AHS interfaced through thyristor based control module and the software details of the intelligent control algorithm developed to produce the required manipulated signals to be fed to a thyristor based control unit are also discussed. The performance of the closed loop behaviour of intelligent control scheme obtained from the experimental studies is also presented.

The highlights of the work done and the directions for further research are given in Chapter 6. The details of the numerical solution of the mathematical model developed, hardware and software details of the experimental studies are presented in the appendices.