CHAPTER 1

INTRODUCTION

Acidification of global and aquatic eco-systems due to atmospheric deposition has been the focal point of research in environmental science and policy in the last three decades. Formation of such acidic compounds on the earth's surface is mainly due to the deposition of sulphur and nitrogen oxide compounds. Sulphur is at the core of the most serious air pollution problems in Asia. Sulphur emissions cause urban pollution; they contribute to acid deposition and influence climate change. The worldwide production of sulphur dioxide (SO_2) by human activities (e.g. combustion of high-sulphur-content fossil fuels, metal smelting, sulphuric acid production, and other industrial processes) is estimated to be 1.4 million tons per year. Sulphur dioxide is formed during the combustion of fuels such as coal, coke or oil that contain sulphur.

Although in recent years the amount of SO_2 emitted in developed countries has decreased, it is increasing gradually in a developing country like India. The enormous usage of fossil fuel has resulted in an increase of the world's total SO_2 emission rate during the recent years. Fossil fuel usage does not directly emit acids into the atmosphere. Instead, it releases large amounts of acid precursors, mainly sulphur oxides and nitrogen oxides. When exposed to the atmosphere, these gases react with water to form sulphuric acid and nitric acid. These acids are deposited on the earth's surface in either dry form, such as aerosols during periods of no precipitation, or in wet form, such as air or snow. Acid rains have an adverse impact on forests, freshwater and soils, killing insect and aquatic life-forms as well as causing damage to buildings and affecting human health.

There is a long history of public fear about SO_2 emission which accounts for acid rain formation in the atmosphere. Garg et al (2001) have estimated district and sector level SO_2 emissions for India, which reveal that the total SO_2 emission for India is increased with an annual growth rate of 5.5%. It causes environmental degradation in the form of soil infertility, reduced crop yields and human health effects such as wheezing, chest tightness, shortness of breath, etc.

In most of the Asian countries, sulphur emissions generated from coal combustion, which satisfy at present about 80% of the energy demand. Thus Asian sulphur emission was equal to Europe and North America during 1990s (Foell et al 1995), and it is likely to continue to increase in the following decades (Klimont et al 2001). In India, SO_2 emissions due to consumption of coal have been calculated for the various years in different sectors, including the projections for the future (Mitra & Sharma 2002) as shown in Table 1.1. The main emissions from coal combustion at thermal power plants are carbon monoxide (CO), nitrogen oxide (NO_X), sulphur oxide (SO_X), chlorofluorocarbons (CFC) and Suspended Particulate Matters (SPM) such as fly ash, soot, and other trace gas species. Research is highly essential on population exposure to these polluting gases and these emissions are considered to be responsible for heating up the atmosphere and producing harmful global environment.

The sectoral analysis shows the major percentage of SO_2 emissions taking place due to the coal utilized electric power generators. These industrialized areas burn sulphur containing coal to generate heat and electricity.

Table 1.1 Pollutants emitted (tons/day) from different sectors in India

S.No	Species	Transport sector (tons / day)	Power sector (tons / day)	Other industries (tons / day)
1.	Hydrocarbon (HC)	310	50	6
2.	Suspended Particulate Matters (SPM)	13	50	6
3.	Nitrogen Oxides (NO_x)	157	143	20
4.	Sulphur Oxides (SO_x	111	121	33

The Pollution Control Board (PCB) in India combined with the Ministry of Environment and Forest (MOEF) fixes the standard norms at different rates based on the emission produced by the industry. But it is much difficult to achieve the limit set by MOEF. The reason behind the SO_2 emission is more in India due to the property of Indian coal, which contains a significant amount of sulphur. While burning it produces harmful SO_2 emission into the atmosphere.

Flue Gas Desulphurization (FGD) is the effective and reliable SO_2 removal methodology and it is classified as dry, semidry, and wet FGD process. Among these techniques, wet FGD is the cost effective method (Cofala et al 2004) and produces 60-95% removal efficiency (Liu et al 2008). Different absorbents are used in FGD such as lime (Liu et al 2008), water with ammonia (NH_3) (Ipek et al 2008), and NaOH (Schultes 1998).

Selection of absorber for FGD process is one of the important factor need to be considered for obtaining maximum SO_2 removal efficiency. There are several absorbers proposed by researchers for FGD process such as bubbling jet reactor (Zheng et al 2003), combined packed and spray tower absorber (Gomez et al 2007), cable bundle wet scrubber, and packed column (Colle et al 2005a). Before fabricating the absorbers for SO_2 emission control process, it is simulated with different absorbents using Computational Fluid Dynamics (CFD) (Ebrahimi et al 2003, Marocco & Inzoli 2009, Ruitang et al 2008 and Gomez et al 2007). Based on the results of CFD analysis, a real plant for SO_2 emission control process is developed.

Minimization of SO_2 emissions through active process control of combustion systems has become an important research area. Nowadays, industries require more reliable, accurate, robust, efficient and flexible control systems for the operation of the process plant. In order to fulfil the above requirements, there is a continuing need for research on improved forms of control. There is also a need for a variety of strategies including control system design, for improved process models to represent the plant commonly used in industry. Classical controllers using the Proportional-Integral-Derivative (PID) algorithm are still widely used. However, they can be challenged by process oscillations when large disturbances or set points change.

The technology used in the process industries has been changed rapidly in the recent years as plant processes become more and more complex. These changes are due to the increasing need for better product quality and requirements for minimization of operating costs. As a result, significant new constraints have emerged which reflect directly on plant process technology. Another important factor that contributes to the development of process technology arises from environmental legislation which is frequently revised. In addition, the capability and availability of new and modern hardware and software also play an important role in the advancement of technology.

Previous researchers had problems such as signal transmission delays, relatively low processing power for computational needs and poor signal to noise ratios. However, with the development of the new technology in instrumentation and measurement, more accurate and precise data can be provided. Besides, the introduction of modern computers offers better solutions in terms of speed and capacity. Thus, the researchers and process control developers in the industry utilize these new hardware and software capabilities to improve the existing technology. They play an important role in the development of new controllers as well.

In general, developments in classical control system technology have been based on linear theory which is successful when applied to process systems. Although all the physical systems are nonlinear to some extent, some systems can be approximated in a very satisfactory fashion using linear relationships. However, certain types of chemical systems or processes have highly nonlinear characteristics due to the reaction kinetics involved and the associated thermodynamic relationships. In these circumstances, conventional linear controllers are inadequate to control the performance over an entire operating range. In this situation, it is essential to design a robust nonlinear controller for different operating conditions.

Though there have been significant developments in control systems during the last two decades, the chronic PID controllers are still popular and necessary for industrial processes due to their structural simplicity and reliability. Many research studies on controller tuning have reported that the control loops are not properly tuned when they are implemented, while other loops are not updated sufficiently (Astrom & Hagglund 1984).

The simplicity and transparency of PID control mechanism, the availability of a large number of highly efficient, reliable and cost-effective commercial PID control modules and their acceptance from the operators are the reasons for their popularity. The process of determining the PID controller parameters K_p, T_i and T_d to achieve high and consistent performance specifications is known as controller tuning. In the design of a PID controller, these parameters must be optimally selected in such a way that the closed loop system will give the desired response.

There are many aspects that should be taken into account while designing a PID controller such as asymptotic tracking and disturbance rejection, stability and robustness and transient response control. Many works have been carried out in the case of the first two aspects (Mitra & Bhattacharya 2002) while very few works were reported regarding the transient control problem. However, a good transient response is one of the most important criteria in the design of every control system. The performance of the transient response is commonly measured in terms of time domain specifications such as rise time (t_r), peak time (t_p), peak overshoot (M_p) and settling time (t_s).

Analytical expressions of transient responses were provided for certain class of transfer functions whose poles were all real, negative and distinct (Hauksdottri 1996). The limitations on transient response in terms of poles and zeros of the system were also studied (Middleton & Graebe 1999 and Jayasuriya & Song 1992). The relationships of undershooting step response and non-minimum phase zeros were studied by Mita &Yoshida (1981) and Leon (1994). The design of non-overshooting controllers for discrete systems was proposed by Deodhare & Vidyasagar (1990) and Leon & Salazar (2002). The relationship between the characteristics of polynomial and time domain responses for addressing the transient control problem was reported by Naslin (1968). In the later stage, Manabe (1991) proposed the concept of Coefficient Diagram Method (CDM) to obtain a good transient response which is still considered as an important contribution to transient control problem.

The CDM is an algebraic approach, where polynomial expressions are used to represent the plant and the controller. With the polynomial representation of the plant, the ambiguity that arises due to pole-zero cancellations is avoided. The “simultaneous approach” of CDM helps the designer to define the type and degree of the controller polynomials and characteristic polynomial of the closed loop system at the beginning. The coefficients of the controller polynomials are found later by considering the design specifications. The designer is able to maintain a good balance between the rigor of the requirement and the complexity of the controller due to this simultaneous design concept. Thus, without confronting serious difficulties and necessitating much experience, CDM makes it possible to design very good controllers with less effort and relative ease when compared with the other existing methods (Manabe 1998).

The CDM had been successfully implemented in many fields such as steel mill control (Kessler 1960), gas turbine control (Thanaka 1992), control of robotic manipulators (Ucar & Hamamci 2000), space craft control (Manabe 2001), control of DC motor (Hamamci & Koksal 2001), control of chemical processes such as temperature control (Hamamci & Koksal (2003), Bhaba et al (2005) and level control (Bhaba & Somasundaram 2009). From the literature, it is clear that the CDM is an efficient and fertile control tool which makes the designer to devise a controller under the conditions of stability, robustness and time domain performance. Based on these features, CDM based PID controller is used for SO_2 emission control process.

Though the CDM controller produces better performance over conventional PID controllers, research work has to go a long way in the evolution towards the enhancement of quality and performance. Fractional calculus is the generalization of integer order calculus in which the non-integer orders are included in integrator and differentiator commonly known as λ and μ (Podlubny 1998). Several researchers have used fractional order controller for improving the system quality performances (Monje et al 2007, Das 2009 and Padula & Visiol 2011), since it consists of five parameters involved as tuning parameters such as, Kp, T_i, T_d, λ and μ. Ziglar–Nichols tuning method has been used by researchers for tuning of the parameters K_p, T_i, and T_d of fractional controller with integer approximations (Vinagre et al 2000, Bettoua & Charef 2009). The idea of using fractional calculus for control applications was introduced by Outstaloup (1988). Further the researchers, Gopikrishnan et al (2012) implemented fractional calculus for cart-pendulum system, Chen (2006) for IO (Integer Order) plant with IO controller; IO plant with FO (Fractional Order) controller; FO plant with IO controller and FO plant with FO controller. Sundaravadivu & Saravanan (2012) designed Fractional Order Proportional Integral Derivative Controller (FOPID) for the liquid level control of a spherical tank.

The interest in Fractional Order Proportional Integral Derivative (FOPID) controller is justified by a better flexibility, because it has two more parameters, i.e. λ and μ used to fulfil additional specifications for the design or other interesting requirements for the controlled system (Charef et al 1992).

Hence, to enhance the performance of the controller, the present work takes into consideration the merits of both CDM control strategy and fractional calculus and the proposed methodology introduces Fractional Order based CDM [FOCDM-$PI^{\lambda}D^{\mu}$] controller for SO_2 emission control. Also, intensive research work is still underway to suggest techniques for the tuning of λ and μ of fractional order $PI^{\lambda}D^{\mu}$ controller.

An evolutionary computation technique has been developed to obtain global optimal solution in many research areas. Leu et al (2002) proposed a design method for optimizing λ and μ based on specified gain and phase margins with a minimum Integral Squared Error (ISE) criterion. Valerio & Costa (2006) developed two sets of tuning rules for fractional PID controllers based on the Ziegler–Nichols tuning rule. Cao & Cao (2006) developed the parameter optimisation design process using Particle Swarm Optimisation (PSO).

PSO is a stochastic optimization strategy from the family of evolutionary computation, is a biologically-inspired technique originally proposed by James Kennedy and Russell Eberhart in 1995 (Kennedy & Eberhart 1995). PSO has been regarded widely as a promising optimization algorithm due to its combination of simplicity, stumpy computational cost and better performance.

PSO uses a number of agents (particles) that comprise a swarm moving around in the search space looking for the best solution. Unlike genetic algorithms, the PSO updates populations without any genetic operators such as crossover and mutation. Hence in the present study, PSO based tuning algorithm is used to tune the parameters λ and μ of the fractional order $PI^{\lambda}D^{\mu}$ controller.

1.1 RESEARCH OBJECTIVES

The present work focuses o the following objectives to overcome the problems aforementioned.

- Determination of L/G ratio, packed height, diameter and height of the packed column based on mathematical modeling.
- Development of CFD model for a packed column based on physical modelling to ensure the maximum SO_2 removal efficiency.

- Design and development of lab-scale SO_2 emission control setup.
- Approximate the SO_2 emission control system as FOPTD (First Order Plus Time Delay) transfer function using experimental step test method by considering 0.1M H_2O_2 and 0.01M H_2SO_4 as liquid reactants with 5000 ppm inlet SO_2 gas.
- To compute the parameters of classical controllers such as CDM based PID controllers (CDM-PID) and Ziegler Nichols PID (ZN-PID) tuning methods using FOPTD model parameters for comparative studies.
- To design and implement the proposed Fractional order based CDM $PI^{\lambda}D^{\mu}$ [FOCDM- $PI^{\lambda}D^{\mu}$] controller in the laboratory scale SO_2 emission control system and compare the performance with the classical PID controllers.
- To validate the performance of FOCDM-$PI^{\lambda}D^{\mu}$ controller with classical PID controllers through experimental studies with pure SO_2 gas.
- To test the performance of FOCDM- $PI^{\lambda}D^{\mu}$ controller over other conventional PI controllers through experimental studies with mixed (SO_2+ NO_2) gas.

1.2 STRUCTURE OF THE THESIS

Chapter 1 introduces background information relevant to this research and highlights the objectives based on the main issues.

Chapter 2 summarizes the established concepts and techniques reported in the literature concerning SO_2 emission control methods. A survey of the existing control techniques applied to SO_2 emission control process, development of CDM based controllers, the history and development of fractional order controllers and PSO algorithm are also reviewed. This chapter concludes by providing a basis or motivation for continuation of the research work.

Chapter 3 describes the mathematical modelling of packed column for SO_2 emission control, CFD modelling and analysis using water and hydrogen peroxide absorbents.

Chapter 4 illustrates the configuration of laboratory SO_2 emission control experimental setup. The packed column, measuring techniques, data acquisition and model identification techniques adopted are also presented.

Chapter 5 provides the design and implementation of CDM-PID control strategy and the design of proposed fractional order based CDM $PI^{\lambda}D^{\mu}$ [FOCDM- $PI^{\lambda}D^{\mu}$] controller strategy in the laboratory experimental set up. The performance, robustness and disturbance test of the proposed controller are also demonstrated. Comparative studies are carried out with the existing classical control techniques to highlight the performance of the proposed controller for pure SO_2 with 5000 ppm concentration as an input to the experimental system.

Chapter 6 emphasizes the Fractional Order based CDM PID [FOCDM- $PI^{\lambda}D^{\mu}$] controller strategy with mixed gas (SO_2 with 5000 ppm +NO_2 with 1000 ppm concentration) as an input to the experimental system.

Chapter 7 summarizes the major conclusions of the research work and suggests the scope for further work. Various sources pertaining to this research work are listed in the references and additional supporting details are given in the appendices.