CHAPTER 2

LITERATURE REVIEW

The chapter reviews the literature related to the design of packed column, development of polynomial based controllers with CDM control strategies, and fractional order controllers for SO_2 emission control process.

2.1 SO_2 EMISSION CONTROL TECHNIQUES

This section covers the important concepts and techniques published in the literature concerning SO_2 emission control process. It is an interesting and challenging research problem which has led to a large number of motivating and interesting published papers. Before the industrial revolution, the main SO_2 emission sources of the atmosphere were from volcanoes (Andres & Kasgnoc 1998) and the oxidation of reduced sulphur compounds produced by oceanic phytoplankton (Bates et al 1992). The emissions of SO_2 into the atmosphere have increased enormously in the last 150 years due to the production and combustion of sulphur-containing fuels (Lefohn et al 1999, Stern 2005).

The main sources of SO_2 emissions are coal fired boilers, sulphuric acid plants, chemical and metallurgical furnaces. Among these, power sector plays a major role in producing sulphur emissions into the atmosphere (Shrestha et al 1997). In Industry, coal and oil emit SO_2 as a flue gas during the combustion process. It poses many threats and is likely to cause environmental and human health effects.

Rubin et al (2004) detailed about the government actions to reduce SO_2 emission and quantitatively characterised historical trends in the deployment and costs of Flue Gas Desulphurisation (FGD) technologies. Over the past 30 years, they used these data to develop quantitative 'experience curves' to characterise the rates of cost reduction as a function of cumulative installed capacity of each technology. The SO_2 capture efficiency of FGD systems has continued to improve markedly over the past two decades. As a result, new plants frequently face more stringent control requirements commensurate with this improved technological capability. FGD system is the most widely used environmental technology for high-efficiency removal of SO_2 at coal-fired electric power plants. Though FGD system is the most expensive environmental technology, substantial decreases in capital costs have been realised over the past several decades as a result of investments in research and development, learning by doing at power plant facilities, competition among equipment manufacturers and other factors.

Dong et al (2003) investigated the removal of sulphur dioxide from automotive exhausts and gases generated by combustion of fossil fuels. They developed a chemical kinetic model to analyse the time evolution of the different main species involved in the flue gas, initially stressed by a single pulse corona discharge at the atmospheric pressure and at 300K temperature. The results pointed out that, the sulphur dioxide is removed by reacting with OH radicals and produces sulphuric acid. The removal rate of SO_2 increased with increasing water vapour and oxygen content in the flue gas signifying that OH radical is the main source for SO_2 removal process.

Cofala et al (2004) presented a model for integrated assessment of acidification in Asia used to identify the cost-effective emission control strategies. These strategies helped to achieve environmental targets for ambient SO_2 concentrations and sulphur deposition at the least cost. The results demonstrate a potential for significant cost savings in Asia, if emission controls are allocated to those sources that have the largest environmental impact and are cheapest to control. Combining the results from the dispersion calculation with the population database model, it is estimated that in 2020 more than 1.1 billion people will live in areas where SO_2 concentrations will exceed the WHO (World Health Organisation) guideline. The number of people whose lives are threatened is expected to increase by 60% despite the recent improvements in emission control legislation. Since health damage from SO_2 emissions can reach significant dimensions in economic terms further control of SO_2 emissions in Asia will be necessary.

Streets et al (2001) reviewed recent development of sulphur emissions in Asia since industries experienced a rapid increase in energy use and as a consequence, emissions of air pollutants. It was estimated that SO_2 emissions in Asia grew from 17.1 million tons in 1975 to 38.5 million tons in 1995, i. e. with an average annual growth rate of 4.1%.

Taylor et al (2005) described an overview of government actions and technology development for SO_2 emission control. In order to reduce the sulphur emissions, Wet Flue Gas Desulphurization (WFGD) technique is practiced in a large number of industries. The experience curve shows that most usage of wet type FGD technique is increased in number world wide. Based on the progress ratio in organisational learning curve analysis, 83% of maintenance and supervision cost was reduced by WFGD process. The number of class based patents on SO_2 emission has increased rapidly in the recent years. Of these patents, post combustion technology was used in 53% of patents and pre-combustion technology was used in 17% of the patents.

Azargohar & Dalai (2006) submitted a work on reduction of sulphur dioxide emission from natural gas such as hydrogen sulphide using activated carbon. Hydrogen sulphide is the most important sulphur compound in natural gas and it can be removed by activated carbon using direct oxidation reaction at temperatures less than 200^oC. The data presented in this work indicate that the performance of the catalyst can be improved for the oxidation of hydrogen sulphide, by changing the surface chemistry of carbon.

Alpbaz et al (2006) used lime ($CaCO_3$) solution for the removal of the SO_2 from air. The neutralization of $CaCO_3$ with H_2SO_4 was realized experimentally at the pH value where the dissolution rate is high. The dissolution rate of the limestone and dynamic properties of this system were observed in a jacketed batch reactor. The experiment was initiated by the addition of limestone to pure water. The pH value of the medium was controlled by utilizing self-tuning PID algorithm. A Pseudo-Random Binary Sequence (PRBS) was utilized as a forcing function in order to identify the dynamics of the process to be controlled and the system output was measured. The tuning parameters of the self-tuning PID controller were determined by ISE and IAE criteria.

Thomas et al (2003) delineated the FGD process designed with packed column. The authors developed a lab scale model based on the theory of absorption with chemical reaction. For this purpose, hydrogen peroxide with sulphuric acid was used as a reactant to produce maximum SO_2 removal efficiency. The results ensured that the absorption rate increased with the variation in the hydrogen peroxide concentration. The present investigation clearly shows that the absorption performance increases with the increase in hydrogen peroxide concentration and decreases with the increase in concentration of sulphuric acid. The presence of hydrogen peroxide makes the treatment of flue gas feasible and provides a valuable and highly concentrated sulphuric acid.

Zhou et al (2009) presented a study using hydrogen peroxide solution to humidify calcium hydroxide particles to improve the absorption of

SO_2. It also helped in achieving higher removal efficiency and investigated valuable reuse of the reaction product from the semidry FGD process. Experiments were carried out to inspect the effect of operating parameters including hydrogen peroxide solution concentration, Ca/S molar ratio and approach to adiabatic saturation temperature on SO_2 removal efficiency in a laboratory scale spray reactor.

Colle et al (2004) conducted an experiment for measuring SO_2 removal efficiencies in a pilot-scale column packed with pall plastic rings with sulphuric acid solutions mixed with hydrogen peroxide as the scrubbing liquid. A quite acceptable agreement was found between kinetic parameters deduced from the tests achieved in laboratory and pilot-scale columns. The model was developed based on mathematical correlations to provide good predictions of the absorption performances of industrial columns. It proved to be useful in designing scrubbers for SO_2 abatement with hydrogen peroxide. Hence this absorbent is used in the proposed work.

Colle et al (2005a) examined the absorption of sulphur dioxide in aqueous solutions containing hydrogen peroxide. They investigated liquid-phase reaction of SO_2 for different H_2O_2 and H_2SO_4 concentrations. The experimental data were modelled depending on the H_2O_2 concentration at a given acidity. A satisfactory agreement was attained between experimental results and predictions of models including original values of kinetic parameters.

Colle et al (2008) delved into the SO_2 absorption of fairly and strongly concentrated sulphuric acid solutions, with the addition of hydrogen peroxide, in a cables-bundle lab-scale scrubber at 35 and 50°C. The global kinetic parameter was determined in this study which is essential for the simulation of industrial scrubbers for SO_2 abatement with acid solutions containing H_2O_2. The aim of this study was to obtain the overall kinetic parameter at higher temperatures, namely 35 and 50°C. A correlation (Arrhenius-type correlation) between the overall kinetic parameter and the H_2SO_4 concentration of the scrubbing solution was obtained, by conducting absorption experiments in the laboratory scrubber. With the developed rate-based steady-state model, the values of the kinetic parameters at three different temperatures were simulated in a wider range of practical industrial operating conditions.

Pfeffer & Copenhafer (2011) patented the WFGD process using hydrogen peroxide as an absorbent. This invention relates to the SO_2 flue gas desulphurization process that uses a recirculating aqueous gas scrubbing stream containing sulphuric acid and hydrogen peroxide, from which gypsum was recovered as a by-product. In flue gas desulphurization process, SO_2 containing flue gas stream was contacted with a recirculating stream of an aqueous medium containing concentrated sulphuric acid and hydrogen peroxide. It yielded additional sulphuric acid in the aqueous medium.

2.2 PACKED COLUMN DESIGN AND CFD ANALYSIS

Ebrahimi et al (2003) developed a rate-based model of a counter-current reactive absorption/desorption process for the absorption of SO_2 into sodium carbonate in a packed column. Numerical approach was described to calculate the absorption rate of SO_2 into sodium carbonate solutions. The developed model was capable of predicting the transfer rates of absorption and the enhancement factors. Also, the model could predict the concentrations of all chemical species at any point of the absorption column. The model was validated using a SO_2 absorption process in aqueous sodium bicarbonate solutions.

Ipek et al (2008) experimented with synthetic wastewater containing NH_3 which was sprayed down, as flue gas moved up in the scrubber and reaction between SO_2 and NH_3 took place. SO_2 concentration was decreased from about 1000 ppm to 0 ppm, 36 ppm, 49 ppm and 66 ppm at ammonia (NH_3) concentrations of 328 mg/l, 88 mg/l, 32 mg/l and 9 mg/l respectively. This process could be used for both the SO_2 removal and the wastewater neutralization.

Zheng et al (2003) developed a pilot plant experimental set up down scaled from a 285 MW coal fired thermal power plant. A bubbling jet reactor was used as an absorbent device for lime stone based gypsum producing wet FGD process. Based on this process, SO_2 removal efficiency was increased from 66.1% to 71% when the reactor slurry pH was increased. The temperature increased from 296 to 323 K and caused the reduction in SO_2 removal efficiency from 69.4% to 68.1%.

Gao et al (2008) described the absorption process of SO_2 into limestone slurry with a spray scrubber. The physical performance of the spray liquid in the scrubber and the chemical reactions involved in the scrubber were analyzed in the developed model. It was found that there was a remarkable influence on the concentration of the other elements in the process of SO_2 absorption. Computational Fluid Dynamics (CFD) tool was used to perform several simulations which describe the effects of variables on SO_2 absorption. The results of numerical simulation have provided a basis for design and optimization of the spray scrubber.

Gomez et al (2007) presented a CFD model for a flue-gas desulphurisation plant. The FGD plant is of wet scrubber type with co-current and counter-current sections. The absorbent used was limestone and after the reaction it was converted into gypsum. Simulation studies were conducted and the model developed was applied to the FGD plant. The boiler section in the power station was fired with 4.5 percent high-sulphur coal, and the FGD system has been designed for a desulphurisation capacity of 1.4 million Nm^3/hr with the desulphurisation efficiency of more than 90 percent.

Marocco & Inzoli (2009) concentrated on the gas and liquid hydrodynamics inside an open spray tower simulated using CFD. A model has been developed and implemented into a commercial CFD code to calculate the absorption rate of sulphur dioxide into the limestone slurry. Besides SO_2 absorption, the model also evaluated the evaporation of slurry droplets and the droplet-wall interaction. A pilot plant open spray tower has been analyzed in CFD simulations and the results have been compared with the available experimental data. The main geometrical dimension of the pilot plant absorber was designed as a 3D geometry and it was considered in the CFD simulation analysis. A pilot plant open spray tower has been simulated and the mathematical results show good agreement with the experimental values. Aqueous phase chemistry considers instantaneous equilibrium reactions of eight dissolved species into a slurry droplet, namely SO_2, CO_2, OH^-, HSO_3^-, SO_3^{2-}, HCO_3^-, CO_3^{2-}.

Marocco (2010) developed a CFD model of a counter-current open spray tower desulphurisation reactor. ANSYS-FLUENT 6.3.26 was used to develop the modules for sulphur dioxide absorption. The developed model has been used to simulate a full scale industrial open spray tower operating at different conditions by varying the amount of the injected slurry flow. The absorbents used in a packed column are water and limestone that are sprayed downward from different heights. Thereby sulphur dioxide was washed out of the gas. The two-phase gas–liquid flow in the packed column was simulated with an Euler–Lagrange approach. Physical absorption was modelled using dual film theory and suitable empirical correlations. The developed model was used to simulate an industrial plant at different operating conditions. The results produced are in good agreement with the measured values of sulphur removal efficiency.

2.3 COEFFICIENT DIAGRAM METHOD (CDM) BASED CONTROLLERS

The literature review for the polynomial based controllers based on CDM has been furnished in this section. The subsequent sections delineate some of the important issues related to the development of CDM controllers and engineering applications of CDM based control strategy.

Despite the significant developments in control theory and technology, the ubiquitous PID controllers are still extensively used in industrial applications. A recent literature study reveals that 90% of control loops involve PID controllers, because they perform better for a wide class of processes. They give robust performance for a wide range of operating conditions. Also, it is easy to implement using analog or digital hardware.

Further, Marlin (1995) pointed out that the simplicity, availability, reliability and cost affectivity are the primary factors for the success of PID controllers. Owing to the popularity of PID controllers, many researches devoted their efforts to the development of PID controllers resulting in enormous publications on this topic including a wide variety of design and tuning methods.

In all the aforesaid methods, the main purpose has been to design a controller that performs well. On the other hand, in many practical cases, the control system has to be designed to satisfy the desired performance characteristics. Mostly, the characteristics of the control system are expressed in terms of transient response performance. The transient performance was generally specified in terms of the rise time, settling time, peak time and maximum overshoot (time domain quantities). The time domain specifications are quite important, because most control systems are time-domain systems and they are expected to exhibit acceptable time responses. This means that the control system should be modified until the transient response is satisfactory. Transient performance of the control system directly depends on the controller parameters. Regarding this point, many prominent researches presented the idea of designing PID like controllers by adopting the concept of CDM, which had proved effective for transient response control.

A survey of literature relating to the design of PID like controllers based on CDM is listed below: The performance of the Proportional Integral Derivative Acceleration (PIDA) controller designed by Jung & Dorf (1996) was improved by adding a pre-compensator. Young et al (2001) proposed the method of including pre-compensator to the controller for fast rise time and low overshoot. The parameters of the PIDA controller were designed using CDM. The equivalent time constant and stability index of the CDM were determined experimentally and not mathematically. They conducted simulation for three third order plants of Type 1, 2 and AC induction motor. It was found that PIDA controller of Jung and Dorf method delivered fast response but overshoot occurred. In the case of CDM based PIDA controller, there was no overshoot but the response time was much delayed.

Wu et al (1998) presented a simple torque control method of a two-mass resonant system. The torque controller used a PID controller with smaller gains and in the feedback, a proportional compensation was used. This control method was termed PID-P control. The gains of this PID-P controller were assigned based on CDM technique. The effectiveness of the proposed control method was shown by both simulations and experiments. The results indicated that the designed PID-P torque controller yielded a robust stability even on the load inertia. But the closed loop response was found to have an overshoot with a long rise time. The design was time consuming as it involved complex mathematical calculations. So this was considered as a drawback of this design.

Kumpanya et al (2000) introduced a new PI controller design based on CDM approach. They included a feed forward controller in the closed loop system. The feed forward controller was found to have a phase lead structure with two tuning parameters α and T_d. The T_d was found using ZN technique with the process parameters obtained from the process reaction curve. To retain the phase lead structure of feed forward controller, the value of α was made greater than one. The proposed controller was tested through simulation along with a level process. From the results, it could be seen that the control system with feed forward controller had got time response with an overshoot of 25% less than the system without feed forward controller. The disturbance rejection capability was tested and it was found that the speed of damping the disturbance was the same for the control system with or without feed forward controller. However, the transient response with the proposed method still had a long rise time. In addition, the designer had to perform extra calculations to design the feed forward controller.

Benjanarasuth et al (2002) extended the work of Kumpanya et al (2000). In their work, they modified the feed forward controller structure with an additional tuning parameter β. The controller designed using CDM along with this modified feed forward controller structure was tested along with a thermal system. On evaluating the system performance, it was found that the proposed control scheme gave a fast response when compared to the control system without feed forward controller. However, computing the parameters of feed forward controller was complex and time consuming.

Khuakoonratt et al (2003) implemented the design of Integral-Proportional Derivative Acceleration (I-PDA) control system which was utilized especially for third order plant. To improve the response speed of the control system, a feed forward controller with a tuning factor α was added to the control system. The parameters of I-PDA controller and feed forward controller were based on CDM design factors. The efficiency of the proposed controller was investigated for three third order plants with different types of system and also for an AC induction motor. From the step response, it was shown that the I-PDA control system with feed forward controller improved the speed of response and proved better than the system without feed forward controller. The time response of both control systems caused a slight overshoot. The effect of tuning parameter α on the system response was studied and the report revealed that for the large value of α, the response was faster but overshoot occurred. The effect of output disturbance was completely rejected by using this control system. However, the drawback of this control scheme was not applicable to the system other than third order plant.

Numsomran et al (2004) developed the control system design for a quadruple tank process via CDM. Using Relative Gain Analysis (RGA) method, the input-output paring for non-minimum phases was made. In this work, an I-P controller was designed by adopting the CDM concept. The step response of the designed controller was compared with that of PI controller tuned by relay feedback method. The proposed controller produced a good response with a little overshoot and fast rise time and thus proved better than the other controller. When the system parameters changed, the I-P controller was found to be robust.

Pattanavijit et al (2006) reported a simplified design of PI controller to govern the speed of two inertia systems using CDM. Initially, the higher order plant model was brought to a lower order model reduction technique. With appropriate values of stability indices, the PI controller parameters were computed for the lower order model. The capability of the PI controller based on the lower order model was examined by employing it to control the original higher order plant model. The effectiveness of the proposed method was confirmed by the simulation results. The ability to reject the effect of output disturbance of the proposed control system was quite similar to the control system using PI controller designed by the direct method.

Hamamci & Tan (2006) established a new method to compute the set of PI controller values that could achieve the desired frequency and time domain specifications. The frequency (gain margin and phase margin) and time domain (t_s and M_p) specifications were defined well before the design. The design was carried out in two steps. In the first step, a global stability region that included all the stabilizing values of the PI controller was determined using the stability boundary locus approach. The local stability region containing the set of PI controller values that satisfied the specified gain margin and phase margin was identified within the global stability region. In the second step, CDM technique was used to determine the set of PID controller values that achieved the desired time domain specifications. They also designed the system using a First Order Plus Dead Time (FOPDT) model of the plant. Explicit formulations between the PI controller parameters and time domain specifications were obtained. By combining these two steps, a graphical representation called the Frequency Time Domain performance (FTDP) map was obtained. The designer could easily obtain the set of PI controllers that attained the desired frequency and time domain performances using this FTDP map.

Budiyono & Sudiyanto (2007) presented the formulation of the controller for scale helicopter in the algebraic frame. In this work, CDM was effectively used to design the characteristic polynomial and compute the controller parameters simultaneously with due consideration of the performance specifications and constraints imposed on the controller. The work demonstrated the implementation of CDM based LQR technique to the MIMO problem.

Benjanarasuth et al (2007) proposed the design of two degree of freedom PID controller based on CDM. The PID tuning formulas were derived based on the approximated plant model and the CDM algebraic equations. The control scheme was tested with a FOPTD model and the results were compared with ZN-PID and Kotaki et al (2005) optimization PID techniques. It was found that the proposed PID control scheme gave improved performance but it was difficult to tune the controller parameters. To obtain the tuning parameters, the critical gain and critical period of the plant or process had to be obtained experimentally following the ZN closed loop tuning method. The control scheme could be applied to only stable first order processes and the use of higher order Pade Approximation (PA) technique for approximating the time delay of the process made the design complicated.

Hamamci et al (2007) developed a Two Degree Of Freedom (2DOF) control structure to control the transient response of an Unstable First Order Plus Time Delay (UFOPTD) system. The control structure consisted of a main PID controller and the parameters were derived based on CDM design key factors. To specify the key factors, a new graphical optimization technique was developed. The parameters of the forward controller depended directly on the main PID controller and there was no need for the designer to do extra calculations. Closed loop simulation results were obtained to illustrate the effectiveness of the developed method. The results proved the effectiveness with an improved time response and a satisfactory disturbance rejection response. The most important feature of the present approach was that it could be applied to control a class of systems.

Bhaba & Somasundaram (2008) designed a PID controller to improve the performance of transient response for a class of SISO systems. The explicit PID tuning formulae were derived by considering CDM as the base. Based on the experimental models, the CDM based PID controllers were designed and tested through simulation. The results were compared with conventional PID controller methods and it was found that the designed control scheme yielded a fair response to set point change and for parametric uncertainties. In the final test, the responses of the control system to different types and magnitudes of the reference input signals were also investigated. It favours the proposed scheme.

Bhaba & Somasundaram (2009) introduced a new CDM based control strategy for a process that exhibited severe static nonlinear characteristics. Based on the polynomial approach (CDM), the elements of the controller were designed. Real time implementation of this control strategy was carried out in a Conical Tank Liquid Level Maintaining System (CTLLMS). The system performance for set point tracking and load disturbance rejection at different operating stages was analyzed. In addition, robustness of the controller was investigated. From this work, it became clear that the new CDM control technique worked well for nonlinear systems.

Somasundaram & Bhaba (2009) presented a new method of designing Proportional Integral-Proportional Derivative (PI-PD) control strategy to inherit the properties of CDM. The PI-PD controller parameters were expressed in terms of CDM controller polynomials. The new control strategy was found to be very simple and easy. Closed loop simulation results of an unstable process with the control scheme gave excellent performance over the other PI-PD tuning method. The highlight of this work was that the new CDM-PI-PD control strategy could be applied to an extensive class of processes.

Somasundaram & Bhaba (2010) established a new Proportional Integral-Proportional (PI-P) control strategy to enhance the performance of the Proportional Integral Controller. A systematic procedure for the CDM-PI-P controller design was presented. The efficiency of the new controller was tested to control an unstable bio-reactor process. The closed loop simulation results proved that the control strategy showed enhanced performance when compared to conventional PI controller.

Bhaba et al (2005) focused on the design and real time implementation of CDM based PID control strategy to an air flow temperature system. The system exhibited severe static nonlinear characteristics. They constructed a Wiener Model based PID control structure by way of admitting the static nonlinearity in the control loop. The parameters of the PID controller were expressed in terms of CDM controller polynomials. The performance and the robustness of the CDM-PID controller were evaluated in real time. The servo and regulatory results of the control strategy were compared with the other Wiener Model based PID controllers.

2.4 FRACTIONAL ORDER CONTROLLERS

The literature review for Fractional Order PID (FOPID) controller is given in this section. This section constitutes historical background, engineering applications of fractional order controllers, development of FOPID controllers and tuning of FOPID controllers.

2.4.1 Historical Background

Fractional order controller is defined as controller described by fractional differential equations. Das (2008) detailed in his book that fractional calculus is three centuries old as the conventional calculus, but not very popular among science and/or engineering community. In a letter dated

30th September 1695, L'Hopital wrote to Leibniz asking him if he had used in his publication the n^{th} derivative of a function $D^n f(x)/Dx^n$ i. e. what would be the result if $n = 1/2$. Leibniz's response was that, "An apparent paradox from which one day useful consequences will be drawn." With these words, fractional calculus was born. During the twentieth century, abundant applications have been found. However, these applications and mathematical background nearby fractional calculus are far from paradoxical. While the physical meaning is difficult to grasp, the definitions are no more accurate than integer order counterpart. Fractional order systems, or systems containing fractional derivatives and integrals, have been studied by many in engineering and science diciplines.

Riemann– Liouvelle (RL) fractional derivatives are some functions, which are used very often. In most cases, the order of differentiation defined as 'λ' may be a real number, so replacing it with λ gives Riemann–Liouville fractional integral defined as 'μ' should be taken between 0 and 1, and λ should be properly composed with integer order derivatives. One of the basic functions of the fractional calculus is Euler's Gamma function. This function generalizes the factorial n! allowing 'n' to take non-integer values.

Several researchers practised fractional order controllers for various applications by formulating solutions using sequential fractional derivatives. The demands of modern technology require a certain revision in the well established mathematical approach. In many applications, fractional derivatives are used for better description of material properties.

Dannon (2009) obtained the fundamental theorem of the fractional calculus in the arithmetic means calculus and inferred fractional derivatives in the arithmetic means calculus. The developed derivation and interpretation can be extended to fractional derivatives in any other power mean calculus. Also the definition of fractional product integral and the fractional product derivative are obtained and proved the fundamental theorem of the fractional calculus.

Chen (2006) detailed about fractional order control structures for four situations. They are 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. The existing proofs have confirmed that the best fractional order controller can do better performance than the best integer order controller. Fractional order PID controller tuning has reached a developed state of practical use. Since (integer order) PID control rules the industry, FO-PID will gain increasing impact and wide acceptance. Furthermore, based on some real world examples, fractional order control is everywhere when the dynamic system is of distributed parameter nature.

Millor & Ross (1993) practised the same way for sequential fractional derivatives and they clearly detailed the difference between Riemann – Liouville differentiation and sequential fractional differentiation. Leibinz rule is essentially useful for the evaluation of polynomial based functions with known fractional derivative.

The new models developed based on non- integer order provides more adequate results than the integer order. Fractional differential and integral order provided a powerful tool for the description of memory and hereditary properties of different substances.

2.4.2 Fractional Order Control for Engineering Applications

The idea of using fractional calculus for control applications was introduced by Outstaloup (1988) who developed a CRONE is the French acronym of Commande Robuste deOrdre Non Entier controller and implemented it in various applications.

Gopikrishnan et al (2012) implemented fractional calculus for cart-pendulum system as a typical benchmark problem for testing various control algorithms. It is a Single Input Multi Output (SIMO) system which has two output variables to be controlled (pendulum-angle and cart-position) using a single input (input voltage to power amplifier). The controllers are tuned for the desired loop-shaping requirements by formulating constrained optimization problem so as to meet the required cart-position and inverted pendulum status.

Kesarkar & Selvaganesan (2011) presented generality for tuning of PI^{λ} /PD^{μ} for universal plant structure. Generalization of these methods to deal with any generalized fractional order plant structure minimizes the tuning efforts considerably. The following plant structure cases are considered for analysis: First Order Plus Dead Time (FOPDT), Second Order Plus Dead Time (SOPDT) and fractional order plant. MATLAB simulation results for 3 different plant cases verify the usefulness of the proposed generalization.

Karanjkar et al (2012) also reviewed the recent trends in fractional order controller and ongoing research on tuning of its parameters. Using n integer toolbox with MATLAB/SIMULINK, series and parallel connected fractional order PID controllers have been designed for first-order system and simulation results are compared with conventional controllers. The results ensure that the application of fractional order calculus in controller design introduced superior performance to the conventional controller.

Vaithiyanathan & Bhaba (2013) designed a fractional order PI controller (PI^{λ}) for an integer order air flow temperature system and implemented it in real time. Controller parameters K_P & K_I are derived from the Fractional Order Characteristic Polynomial (FOCP) in terms of frequency ω and fractional order λ. A construction of global stability region in K_P - K_I plane is done and the best operating settings of K_P and K_I are identified by an optimization technique. Real time runs with these controller settings K_P and K_I are carried out for various set point tracking and load rejection.

2.4.3 Tuning of Fractional Order Controllers

This section reviews literature background regarding tuning of fractional order PID controllers.

Chen et al (2008) presented a new practical tuning method for Fractional Order Proportional and Integral (FO-PI) controller. The plant to be controlled is a first order plus delay time (FOPDT) system. Generalization of constrained integral based controller tuning method was used to handle the FO-PI controller. The main design objective of this tuning method is load disturbance rejection. Load disturbances are low frequency signals and their attenuation is a very important feature of a controller. By maximizing the integral gain, the effect of load disturbance at output will be minimum. Load disturbance is defined by integrated absolute error and maximizing integral gain will minimize the error. In this paper, ISE is used for tuning rule development. For a given FOPDT model of a system, if the relative dead time is very small, then it has been observed that a fractional PI controller of order $\lambda = 0.7$ is found to outperform the IO counterparts. For systems with relative dead time close to unity, it has been observed that $\lambda = 1.1$ speeds up the response compared to the sluggish IO counterparts. However, with the disadvantage is that there was a higher overshoot in the performance of the process.

Bettoua & Charef (2009) developed a conception method for fractional $PI^{\lambda}D^{\mu}$ controller. The new tuning method was based on the classical Ziegler–Nichols tuning method for setting the parameters of the fractional $PI^{\lambda}D^{\mu}$ controller. This means setting the parameters of the classical PID controller, and on the minimum integral squared error criterion by using the

Hall–Sartorius method for setting the fractional integration action order λ and the fractional differentiation action order μ. Illustrative examples and simulation results were presented to show the control quality enhancement of fractional $PI^{\lambda}D^{\mu}$ controller, compared to the PID controller using Ziegler–Nichols tuning method. From the simulation results, it was found that the fractional $PI^{\lambda}D^{\mu}$ controllers have significantly improved the performance characteristics of the feedback control systems compared to the classical PID controllers.

Sundaravadivu & Saravanan (2012) designed Fractional Order Proportional Integral Derivative Controller (FOPID) for liquid level control of a spherical tank which was modelled as a First Order Plus Dead Time (FOPDT) system. The $PI^{\lambda}D^{\mu}$ controller was designed using minimization of Integral Square Error (ISE) method. The response of FOPID controller was compared with the integer order PID (IOPID) controllers in simulation and with experimental setup. This method offers a practical and systematic way of the controllers design for the considered class of FOPDT plant. From the simulation and experimental results, it was observed that the designed fractional order controller works more efficiently with improved performance when compared with the integer order controller.

Monje et al (2007) detailed that there are many different ways of finding approximations for λ and μ. It is not possible to say which one of them is the better, because even though some of them are better than others in regard to certain characteristics, the relative merits of each approximation depend on the differentiation order, on whether one is more interested in an accurate frequency behaviour or in accurate time responses, on how large admissible transfer functions may be and other factors like these. They also proposed an auto-tuning method for fractional order $PI^{\lambda}D^{\mu}$ controller based on the specifications of gain crossover frequency, phase margin and damping property of the time response of the system. The experimental platform has been designed and tested with the fractional order controllers designed by the optimization tuning methods. The platform consists of a low pressure flowing water circuit which is bench mounted and completely self contained.

Padula & Visiol (2011) proposed a new set of tuning rules for PID and FO-PID controllers based on the minimisation of the integrated absolute error. It yields a low overshoot and a low settling at the same time, subject to a constraint on the maximum sensitivity. By comparing the results obtained from PID and FO-PI controllers, fractional-order integral action was not advantageous, while the use of a fractional-order derivative action provides a performance improvement.

Padhee et al (2011) studied the designing of FOPID controller to determine the two key parameters λ and μ apart from the usual tuning parameters of PID using different tuning methods. Both λ and μ are in fraction which increases the robustness of the system and provides an optimal control. Genetic algorithm is used as a tuning method for tuning λ and μ of FOPID controller. In PID controller, where the main objective was to find out the optimal set of values of K_p, K_i and K_d, whereas in fractional order PID controller the objective is to find out the optimal values of λ and μ. If λ and μ are altered, they affect the unit step response of the system.

Maiti et al (2008) focused on the optimization of integer order PID and fractional order PID controller parameters by PSO algorithm. Fractional order PID controller generalizes the integer order PID controller and expands it from a point to a plane. This expansion adds more flexibility to the controller design and is used to control real world processes more accurately. After running the PSO algorithm a large number of times, it was found that almost all the particles had fitness value very close to zero. It is noted that for the given common performance criteria on percentage overshoot and rise time, the fractional order controller achieves better results than its integer order counterpart. The scheme of fractional PID controller design can find extensive commercial application in the next generation controller. The results ensured that fractional order controllers provide better performance over the integer order controllers. Using fractional order PID controllers, there was a significant reduction in the percentage overshoot, rise time and settling time as compared to the integer order PID controllers.

Tang et al (2012) reviewed the design of FOPID controller using Chaotic Ant Swarm (CAS) optimization method. The tuning of FOPID controller originated as a nonlinear optimization problem, in which the objective function consists of overshoot, steady-state error, rise time and settling time. CAS algorithm, a newly developed evolutionary algorithm inspired by the chaotic behaviour of individual ant and the self-organization of ant swarm, is used as the optimizer to search the best parameters of FOPID controller. The designed CAS-FOPID controller was implemented in an Automatic Regulator Voltage (AVR) system. Various numerical simulations and comparisons with other FOPID/PID controllers proved that the CAS-FOPID improved the system robustness with respect to model uncertainties.

Ramezanian (2013) presented a method of tuning the optimal parameters of fractional order PID using PSO algorithm fractional and integer order systems. Using the appropriate fitness function, optimum parameters can be found in less number of iterations. Oustaloup's approximation method uses a band-pass filter to approximate the fractional order operator based on frequency domain response. The basic concept of PSO lies in accelerating each particle toward its local best and the global best locations, with a random weighted acceleration at each step interval. The modification of the particle’s position was mathematically modelled and the searching method of the PSO-FOPID controller was implemented in this research.

Zamani et al (2009) developed a design method for determining the FOPID controller parameters using the PSO algorithm. The method involves a new time domain and frequency domain performance criterion. Application of the method to a practical Automatic Voltage Regulator (AVR) shows that the proposed algorithm can perform an efficient search for the optimal FOPID controller parameters. A new performance criterion in the time domain and frequency domain was proposed for evaluating the FOPID controller that includes overshoot, rising time, settling time, steady-state error, integral absolute error, integral of squared-input, Gain Margin (GM) and Phase Margin (PM).

Most of the literature reviews pointed out in this section used PSO algorithm for optimizing the parameters of λ and μ and hence this technique is considered for the present work.

2.5 SUMMARY AND RESEARCH MOTIVATION

From the above discussion of SO_2 emission control, it is clear that there is a considerable challenge in selecting the absorbent for the packed column to obtain higher SO_2 removal efficiency. Most of the literature studies focused on lime based FGD process (Liu et al 2008) for SO_2 emission control which produces CO_2 as an additional pollutant into the atmosphere. Hence alternate absorbent sulphuric acid with hydrogen peroxide was proposed by Colle et al (2005a, 2005b) for SO_2 emission control process. Hydrogen peroxide is chosen as an absorbent for their study to produce a by-product without generating the effluent to the atmosphere.

Based on the results given by Colle et al (2005a), concentration of hydrogen peroxide has the direct influence on SO_2 outlet concentration. Also, hydrogen peroxide is less toxic, safe for storage, non-pollutant and it is easily decomposed into water and oxygen. Increase in concentration of sulphuric acid reduces the SO_2 removal efficiency. Hence hydrogen peroxide is externally added and it depends on the changes occurring in the SO_2 outlet concentration. Hence sulphuric acid with externally added hydrogen peroxide is proposed in the current research work.

Further by regulating the flow rate of externally added hydrogen peroxide, it becomes possible to increase the concentration of H_2O_2 in the mixed solution which balances the SO_2 outlet concentration at a minimum level. Hence an advanced and robust controller is essential to regulate the flow rate of externally added hydrogen peroxide in order to achieve maximum SO_2 removal efficiency.

Based on the literature, CDM based PID controller is considered to achieve better control action for SO_2 emission control processes in terms of stability, robustness and time domain specifications. To further enhance the performance of the CDM-PID controller, the concept of fractional calculus is incorporated since it is one of the most recent research applications in control theory for engineering applications. It provides highly accurate control over the processes.

Thus this work has been directed towards the development of a new control strategy by incorporating fractional calculus with the concept of CDM to tune the fractional order PID controller parameters and it is named as Fractional Order based CDM-$PI^{\lambda}D^{\mu}$(FOCDM-$PI^{\lambda}D^{\mu}$) controller. The optimal tuning parameters of fractional integral order (λ) and fractional differential order (μ) are obtained by PSO algorithm.