

## TABLE OF CONTENTS

CHAPTER NO.	TITLE	PAGE NO.
	<b>ABSTRACT</b>	iii
	<b>LIST OF TABLES</b>	xii
	<b>LIST OF FIGURES</b>	xiv
	<b>LIST OF SYMBOLS AND ABBREVIATIONS</b>	xvii
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 RESEARCH OBJECTIVES	9
	1.2 STRUCTURE OF THE THESIS	10
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>12</b>
	2.1 SO <sub>2</sub> EMISSION CONTROL TECHNIQUES	12
	2.2 PACKED COLUMN DESIGN AND CFD ANALYSIS	17
	2.3 COEFFICIENT DIAGRAM METHOD (CDM) BASED CONTROLLERS	20
	2.4 FRACTIONAL ORDER CONTROLLERS	27
	2.4.1 Historical Background	27
	2.4.2 Fractional Order Control for Engineering Applications	29
	2.4.3 Tuning of Fractional Order Controllers	31
	2.5 SUMMARY AND RESEARCH MOTIVATIONS	35

<b>CHAPTER NO.</b>	<b>TITLE</b>	<b>PAGE NO.</b>
<b>3</b>	<b>MODELLING AND ANALYSIS OF THE PACKED COLUMN</b>	<b>37</b>
3.1	MATHEMATICAL MODELLING	39
3.1.1	Determination of $L_m/G_m$ Ratio	41
3.1.2	Determination of Column Diameter	44
3.1.3	Determination of Packed Height and Total Height	46
3.2	CFD MODEL DEVELOPMENT AND ANALYSIS	49
3.2.1	Definition of Geometry	50
3.2.2	Meshing	51
3.2.3	Definition of Physical Modelling	53
3.2.4	Definition of Boundary Conditions	58
3.2.5	CFD Simulation Results	58
3.3	PACKED COLUMN FOR EXPERIMENTAL ANALYSIS	62
<b>4</b>	<b>EXPERIMENTS AND ANALYSIS</b>	<b>64</b>
4.1	EXPERIMENTAL SETUP	64
4.2	INSTRUMENTATION AND MEASUREMENTS	70
4.2.1	SO <sub>2</sub> Gas Sensor with Transmitter	70
4.2.2	Variable Frequency Drive	71
4.2.3	Peristaltic Pump	72
4.2.4	VDPID-03 based Data Acquisition Card	74
4.3	EXPERIMENTAL ANALYSIS	78
4.3.1	Effect of Absorbents on SO <sub>2</sub> Removal Efficiency	78

<b>CHAPTER NO.</b>	<b>TITLE</b>	<b>PAGE NO.</b>
4.3.2	Effect of H <sub>2</sub> O <sub>2</sub> + Externally Added H <sub>2</sub> SO <sub>4</sub> on SO <sub>2</sub> Removal Efficiency	81
4.3.3	Effect of L <sub>m</sub> /G <sub>m</sub> Ratio on SO <sub>2</sub> Removal Efficiency	83
4.3.4	Effect of Packing Material and Packed Height on SO <sub>2</sub> Removal Efficiency	84
4.4	MODEL DEVELOPMENT	86
<b>5</b>	<b>DESIGN AND IMPLEMENTATION OF FRACTIONAL ORDER BASED CDM-PI<sup>λ</sup>D<sup>μ</sup> (FOCDM-PI<sup>λ</sup>D<sup>μ</sup>) CONTROLLER IN SO<sub>2</sub> EMISSION CONTROL PROCESS</b>	<b>91</b>
5.1	DESIGN OF CLASSICAL CONTROLLERS	91
5.1.1	Zigler - Nichols PID (ZN-PID) Controller	91
5.1.2	CDM-PID Controller	92
5.1.2.1	Design of CDM control Strategy	92
5.1.2.2	Computation of CDM-PID controller parameters for SO <sub>2</sub> emission control process	99
5.2	ANALYSIS OF CLASSICAL CONTROLLERS	101
5.2.1	Performance Analysis of ZN-PID and CDM-PID Controllers	102
5.2.2	Robustness Test of ZN-PID and CDM-PID Controllers	103
5.2.3	Load Rejection Analysis of ZN-PID and CDM-PID Controllers	105

CHAPTER NO.	TITLE	PAGE NO.
5.3	FRACTIONAL ORDER PID (FOPI <sup>λ</sup> D <sup>μ</sup> ) CONTROLLER	107
5.3.1	Singularity Function Method	110
5.3.2	Design of FOPI <sup>λ</sup> D <sup>μ</sup> Controller	112
	5.3.2.1 Fractional Integral Order (λ)	112
	5.3.2.2 Fractional Differentiation Order (μ)	113
5.3.3	Optimal Design of λ and μ for FOPI <sup>λ</sup> D <sup>μ</sup> Controller	115
5.3.4	Procedure for Optimizing λ and μ using PSO Algorithm	118
5.4	FRACTIONAL ORDER BASED CDM-PID (FOCDM-PI <sup>λ</sup> D <sup>μ</sup> ) CONTROLLER	119
5.4.1	Design Steps for FOCDM-PI <sup>λ</sup> D <sup>μ</sup> Controller	119
5.5	RESULTS AND DISCUSSIONS	123
5.5.1	First Stage - Performance Analysis	123
5.5.2	Second Stage - Robustness Test	125
5.5.3	Third Stage - Load Rejection Test	127
<b>6</b>	<b>IMPLEMENTATION OF FOCDM-PI<sup>λ</sup>D<sup>μ</sup> CONTROLLER FOR SO<sub>2</sub> EMISSION CONTROL PROCESS WITH MIXED GAS (SO<sub>2</sub> + NO<sub>2</sub>)</b>	<b>129</b>
6.1	PERFORMANCE OF FOCDM-PI <sup>λ</sup> D <sup>μ</sup> CONTROLLER AND CDM-PID CONTROLLERS WITH MIXED GAS	131
6.2	ROBUSTNESS TEST OF FOCDM-PI <sup>λ</sup> D <sup>μ</sup> CONTROLLER AND CDM-PID CONTROLLERS WITH MIXED GAS	133

<b>CHAPTER NO.</b>	<b>TITLE</b>	<b>PAGE NO.</b>
6.3	LOAD REJECTION ANALYSIS OF FOCDM- $PI^{\lambda}D^{\mu}$ CONTROLLER AND CDM-PID CONTROLLERS WITH MIXED GAS	135
<b>7</b>	<b>CONCLUSION AND SCOPE FOR FUTURE WORK</b>	<b>137</b>
7.1	CONCLUSION	138
7.2	SCOPE FOR FUTURE WORK	142
	<b>APPENDIX 1 HARDWARE SPECIFICATIONS</b>	<b>143</b>
	<b>APPENDIX 2 MATLAB CODING FOR OBTAINING CDM-PID CONTROLLER PARAMETERS</b>	<b>148</b>
	<b>APPENDIX 3 MATLAB CODING FOR OBTAINING FOCDM-<math>PI^{\lambda}D^{\mu}</math> CONTROLLER PARAMETERS</b>	<b>150</b>
	<b>APPENDIX 4 MATLAB CODING FOR OBTAINING <math>\lambda</math> AND <math>\mu</math> USING PSO ALGORITHM</b>	<b>153</b>
	<b>REFERENCES</b>	<b>155</b>
	<b>LIST OF PUBLICATIONS</b>	<b>166</b>

## LIST OF TABLES

TABLE NO.	TITLE	PAGE NO.
1.1	Pollutants emitted (tons/day) from different sectors in India	3
3.1	Solubility data for SO <sub>2</sub> absorption in aqueous sulphuric acid	43
3.2	Parameters for CFD analysis	58
4.1	Identified model parameters at different operating points of outlet SO <sub>2</sub> concentrations	90
5.1	ZN-PID controller parameters	92
5.2	Stability indices for standard forms	95
5.3	Performance measures of ZN-PID and CDM-PID controllers at 50 ppm SO <sub>2</sub> outlet concentration	103
5.4	Performance measures of ZN-PID and CDM-PID controllers at 500 ppm SO <sub>2</sub> outlet concentration	105
5.5	Performance measures of ZN-PID and CDM-PID controllers at 50 ppm SO <sub>2</sub> outlet concentration during load rejection analysis	106
5.6	Performance measures of FOCDM-PI <sup>λ</sup> D <sup>μ</sup> and CDM-PID controllers at 50 ppm SO <sub>2</sub> outlet concentration	125
5.7	Performance measures of FOCDM-PI <sup>λ</sup> D <sup>μ</sup> and CDM-PID controllers at 500 ppm SO <sub>2</sub> outlet concentration	126

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE NO.</b>
5.8	Performance measures of FOCDM-PI <sup>λ</sup> D <sup>μ</sup> and CDM-PID controllers at 50 ppm SO <sub>2</sub> outlet concentration during load rejection analysis	127
6.1	Performance measures of FOCDM-PI <sup>λ</sup> D <sup>μ</sup> and CDM-PID controllers with mixed (SO <sub>2</sub> +NO <sub>2</sub> ) gases at 50 ppm SO <sub>2</sub> outlet concentration	132
6.2	Performance of FOCDM-PI <sup>λ</sup> D <sup>μ</sup> and CDM-PID controllers with mixed (SO <sub>2</sub> +NO <sub>2</sub> ) gases at 500 ppm SO <sub>2</sub> outlet concentration	134
6.3	Performance measures of FOCDM-PI <sup>λ</sup> D <sup>μ</sup> and CDM-PID controllers with mixed (SO <sub>2</sub> +NO <sub>2</sub> ) gas at 500 ppm operating point during load rejection analysis	136
A1.1	Peristaltic pump specifications	143
A1.2	SO <sub>2</sub> gas sensor specifications	144
A1.3	General Specifications of VDPID-03 card	145

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE NO.
3.1	Two-film theory	39
3.2	Schematic of packed column	40
3.3	Equilibrium diagram for SO <sub>2</sub> -H <sub>2</sub> SO <sub>4</sub> solubility	43
3.4	Flooding and pressure drop correlation	45
3.5	Colburn diagram	48
3.6	Modelling of a packed column	51
3.7	Solid arrangement of packing material	52
3.8	Wire frame model of packing material	52
3.9	Hypermeshed liquid sprayer	53
3.10	Hypermeshed gas distributor	53
3.11	CFD simulation result for water as an absorbent	60
3.12	CFD simulation result for H <sub>2</sub> O <sub>2</sub> as an absorbent	61
3.13	Photographic view of the packed column	63
4.1	Functional diagram of the experimental setup	65
4.2	Photographic view of the experimental setup	66
4.3	Interfacing diagram	69
4.4	SO <sub>2</sub> gas sensor with transmitter	70
4.5	Variable frequency drive with induction motor	72
4.6	Peristaltic pump	73
4.7	Calibration curve of peristaltic pump	74
4.8	Functional diagram of VDPID-03 card	75
4.9	GUI for experimental work in MATLAB/SIMULINK platform	77



<b>FIGURE NO.</b>	<b>TITLE</b>	<b>PAGE NO.</b>
4.10	SO <sub>2</sub> removal efficiency for various absorbents	79
4.11	Effect of 0.1M H <sub>2</sub> O <sub>2</sub> + various concentrations of H <sub>2</sub> SO <sub>4</sub> on SO <sub>2</sub> removal efficiency	82
4.12	Effect of L <sub>m</sub> /G <sub>m</sub> ratio on SO <sub>2</sub> removal efficiency	84
4.13	Effect of packing material and packed height on SO <sub>2</sub> removal efficiency	85
4.14	Process reaction curve for 20% DAQ opening	87
4.15	Process reaction curve for 40% DAQ opening	87
4.16	Process reaction curve for 60% DAQ opening	88
4.17	Process reaction curve for 80% DAQ opening	88
4.18	Process reaction curve for 100% DAQ opening	89
5.1	Block diagram of CDM control system	92
5.2	Equivalent CDM block diagram	97
5.3	CDM-PID control system	98
5.4	Performance of ZN-PID and CDM-PID controllers at 50 ppm SO <sub>2</sub> outlet concentration	102
5.5	Performance of ZN-PID and CDM-PID controllers at 500 ppm SO <sub>2</sub> outlet concentration	104
5.6	Performance of ZN-PID and CDM-PID controllers at 50 ppm SO <sub>2</sub> outlet concentration during load rejection analysis	106
5.7	Unity feedback control system	107
5.8	Bode plot for the open loop transfer function G <sub>p</sub> (s)G <sub>c</sub> (s) by setting λ=1, μ=1	120
5.9	Convergence graph for fractional order differentiator (μ)	121

<b>FIGURE NO.</b>	<b>TITLE</b>	<b>PAGE NO.</b>
5.10	Convergence graph for fractional order integrator ( $\lambda$ )	122
5.11	Performance of FOCDM-PI $^{\lambda}$ D $^{\mu}$ and CDM-PID controller at 50 ppm SO <sub>2</sub> outlet concentration	124
5.12	Performance of FOCDM-PI $^{\lambda}$ D $^{\mu}$ and CDM-PID controllers at 500 ppm SO <sub>2</sub> outlet concentration	126
5.13	Performance of FOCDM-PI $^{\lambda}$ D $^{\mu}$ and CDM-PID controllers at 50 ppm SO <sub>2</sub> outlet concentration during load rejection analysis	127
6.1	SO <sub>2</sub> emission control setup with mixed gas	130
6.2	Performance of FOCDM-PI $^{\lambda}$ D $^{\mu}$ and CDM-PID controllers with mixed (SO <sub>2</sub> +NO <sub>2</sub> ) gases at 50 ppm SO <sub>2</sub> outlet concentration	132
6.3	Performance of FOCDM-PI $^{\lambda}$ D $^{\mu}$ and CDM-PID controllers with mixed (SO <sub>2</sub> +NO <sub>2</sub> ) gases at 500 ppm SO <sub>2</sub> outlet concentration	134
6.4	Performance of FOCDM-PI $^{\lambda}$ D $^{\mu}$ and CDM-PID controllers with mixed (SO <sub>2</sub> +NO <sub>2</sub> ) gas at 500 ppm operating point during disturbance analysis	135

## LIST OF SYMBOLS AND ABBREVIATIONS

### Symbols

$c_1$ and $c_2$	- Acceleration constants
$A$	- Area of the packed column
$p_{id}$	- Best value of individual particle
$\varepsilon$	- Cell-face void fraction
$P(s)$	- Characteristic polynomial of the closed-loop system
$\alpha_i$	- Characteristic ratio
$a_i$	- Coefficient of characteristic polynomial
$l_i, k_i$	- Coefficients of CDM controller polynomials
$k_1$ and $k_0$	
$C_{SO_2}$	- Concentration of $SO_2$ in liquid
$C_{H_2O_2}$	- Concentration of $SO_2$ in the liquid
$C_{AI}$	- Concentration of solute A at the interface
$C_{AL}$	- Concentration of solute A in the liquid
$\alpha$	- Conservation of mass in each phase (gas and liquid)
$K_c$	- Controller gain
$u$	- Controller signal
$N$	- Degree of polynomial
$D(s)$	- Denominator polynomials of the plant transfer function
$\rho_\alpha$	- Density of phase $\alpha$
$K_d$	- Derivative gain
$T_d$	- Derivative time constant
$S_\alpha$	- Different source terms (drag or body forces)
$\overline{Y}_{\alpha A}$	- Diffusion coefficient
$S_k$	- Droplet mass source

$\tau$	- Equivalent time constant
$y$	- Error in the frequency domain
$\frac{1}{\Gamma(\alpha)}$	- Euler's Gamma function
$D$	- External disturbance signal
$C_f(s)$	- Feed forward controller transfer function
$B(s)$	- Feedback numerator polynomial of CDM controller Transfer function
$K_f$	- Feedback proportional gain
$K_4$	- Flooding factor
$A(s)$	- Forward denominator polynomial of CDM controller Transfer function
$\lambda$	- Fractional differentiation order
$\mu$	- Fractional integral order
$\omega_u$	- Gain cross over frequency
$\rho_g$	- Gas density
$G_m$	- Gas mass flow rate
$V_w^*$	- gas mass flow rate / column cross sectional area
$p_{gd}$	- Global best value
$H_{OG}$	- Height of transfer units
$m$	- Henry's constant
$p_{best}$	- Individual best value
$w$	- Inertia factor
$N_D$	- Integer order of differentiator
$N_I$	- Integer order of integrator
$K_i$	- Integral gain
$T_i$	- Integral time constant
$g_i$	- $i^{\text{th}}$ component of the gravity vector
$\rho_L$	- Liquid density

$L_m$	- Liquid mass flow rate
$\mu_L$	- Liquid viscosity
$\omega_L$	Lower band of crossover frequency
$C(s)$	- Main controller transfer function
$Y_{\alpha A}$	- Mass fraction
$K_{H_2O_2}$	- Mass transfer coefficient in liquid phase
$k_g$	- Mass-transfer coefficient for gas film
$k_l$	- Mass-transfer coefficient for liquid film
$\square$	- Mass-transfer rate from phase $\beta$ into phase $\alpha$
$m_{\beta\alpha}$	
$\omega_{max}$	- Maximum frequency of approximation
$iter_{max}$	- Maximum number of iterations
$w_{max,}$	- Maximum value for inertia factor
$x^{max}$	Maximum value of the particle
$w_{min}$	Minimum value for inertia factor
$x^{min}$	Minimum value of the particle
$X_2$	- Mole fraction of aqueous $H_2SO_4$ entering the column
$X_1$	- Mole fraction of aqueous $H_2SO_4$ leaving the column
$Y_1$	- Mole fraction of $SO_2$ in gas stream entering the column
$Y_2$	- Mole fraction of $SO_2$ in gas stream leaving the column
$Y$	- Mole fraction of $SO_2$ in the gas phase
$X$	- Mole fraction of $SO_2$ in the liquid phase
$N_{OG}$	- Number of transfer unit
$N(s)$	- Numerator polynomials of the plant transfer function
$F(k)$	- Objective function for the FOPID (or) fitness function
$g_{best}$	- Overall best solution
$Z$	- Packed Height
$F_P$	- Packing factor
$P_{SO_2}$	- Partial pressure of $SO_2$ in gas

$P_{AI}$	- Partial pressure of solute A at the interface
$P_{AG}$	- Partial pressure of solute A in the gas
$\Gamma\alpha$	- Phase-diffusion coefficient
$P_i$	- Poles of the rational transfer function
$x_{id}$	- Position of the particle
$G_f(s)$	- Pre-filter element transfer function
$F_{LV}$	- Pressure drop in the packed column
$\theta$	- Process delay
$K_p$	- Process gain
$\tau_p$	- Process time constant
$K_c$	- Proportional gain
$N_{SO_2}$	- Rate of mass transfer of $SO_2$
$N_A$	- Rate of transfer of component A
$R$	- Reference input
$F(s)$	- Reference numerator polynomial of CDM controller Transfer function
$t_s$	- Settling time
$\rho_v$	- $SO_2$ gas density
$K_{SO_2}$	- $SO_2$ gas mass transfer coefficient
$M_{SO_2}$	- $SO_2$ molecular weight
$S_{\alpha A}$	- Source term for chemical reaction in the column
$\gamma_i$	- Stability index
$\gamma_1$ and $\gamma_2$	- Stability indices
$\gamma_i^*$	- Stability limits
$Y$	- System output
$P_{target}(s)$	- Target characteristic polynomial
$P_{TOT}$	- Total pressure in the packed column
$G_P(s)$	- Transfer function model of the P controller
$G_{PI}(s)$	- Transfer function model of the PI controller

$G(s)$	- Transfer function model of the plant
$\vec{v}_\alpha$	- Velocity vector
$r_\alpha$	- Volume fraction of the phase
$Z_i$	- Zeros of the rational transfer function

### Abbreviations

AC	- Alternating Current
NH <sub>3</sub>	- Ammonia
ADC	- Analog to Digital Converter
ANN	- Artificial Neural Networks
AVR	- Automatic Voltage Regulator
CO <sub>2</sub>	- Carbon Dioxide
CO	- Carbon monoxide
CAS	- Chaotic Ant Swarm
CAS-	- Chaotic Ant Swarm - Fractional Order Proportional Integral
FOPID	Derivative
CFC	- Chlorofluorocarbon
CD	- Coefficient Diagram
CDM	- Coefficient Diagram Method
CDM-PI	- Coefficient Diagram Method- Proportional Integral
CDM-PID	- Coefficient Diagram Method -Proportional Integral Derivative
CDM-PI-P	- Coefficient Diagram Method -Proportional Integral- Proportional
CDM-PI-PD	- Coefficient Diagram Method -Proportional Integral- Proportional Derivative
CC	- Cohen Coon
CRONE	- Comman de Robuste de Ordre Non Entier
CFD	- Computational Fluid Dynamics

DAQ	- Data Acquisition
DAC	- Digital to Analog Converter
DC	- Direct Current
EE	- Electrically Erasable
FOPDT	- First Order Plus Dead Time
FGCS	- Flue Gas Cleaning Systems
FGD	- Flue Gas Desulphurization
FO	- Fractional Order
FOCDM- $PI^\lambda D^\mu$	- Fractional Order based Coefficient Diagram Method -PID Controller
FOCP	- Fractional Order Characteristic Polynomial
FO-PI	- Fractional Order -Proportional Integral
FOPID	- Fractional Order Proportional Integral Derivative
FTDP	- Frequency Time Domain performance
GM	- Gain Margin
GUI	- Graphical User Interface
HC	- Hydro Carbon
HCl	- Hydro Chloric acid
pH	- Hydrogen ion concentration
H <sub>2</sub> O <sub>2</sub>	- Hydrogen peroxide
IO	- Integer Order
IOPID	- Integer Order Proportional Integral Derivative
IAE	- Integral Absolute Error
ISE	- Integral Squared Error
ITAE	- Integral Time Absolute Error
I-PDA	- Integral-Proportional Derivative Acceleration
CaCO <sub>3</sub>	- Lime
LQR	- Linear Quadratic Regulator
MCU	- Microcontroller Unit



MOEF	- Ministry of Environmental and Forest
HNO <sub>3</sub>	- Nitric acid
NO <sub>2</sub>	- Nitrogen dioxide
NO <sub>x</sub>	- Nitrogen oxides
PA	- Pade Approximation
PSO	- Particle Swarm Optimisation
PSO-FOPID	- Particle Swarm Optimisation- Fractional Order Proportional Integral Derivative
PC	- Personal Computer
PM	- Phase Margin
PCB	Pollution Control Board
P	- Proportional
PI	- Proportional Integral
PID	- Proportional Integral Derivative
PIDA	- Proportional Integral Derivative Acceleration
PID-P	- Proportional Integral Derivative-Proportional
PI-PD	- Proportional Integral-Proportional Derivative
PRBS	- Pseudo-Random Binary Sequence
PWM	- Pulse Width Modulation
RGA	- Relative Gain Analysis
RL	- Riemann- Liouville
SOPDT	- Second Order Plus Dead Time
SIMO	- Single Input Multi Output
SISO	- Single Input Single Output
NaOH	- Sodium Hydroxide
SO <sub>2</sub>	- Sulphur di oxide
SO <sub>x</sub>	- Sulphur oxides
H <sub>2</sub> SO <sub>4</sub>	- Sulphuric acid
SPM	- Suspended Particulate Matters

2DOF	- Two Degree of Freedom
UART	- Universal Asynchronous Receiver Transmitter
UFOPTD	- Unstable First Order Plus Time Delay
VFD	- Variable Frequency Drive
VSI	- Voltage Source Inverter
WFGD	- Wet Flue Gas Desulphurization
WHO	- World Health Organisation
ZN	- Ziegler Nichols
ZN-PID	- Ziegler Nichols- Proportional Integral Derivative
ZN-PI	- Ziegler Nichols-Proportional Integral