Contents

Certificates		ii-iv
Dedication		v
Acknowledgement		vi
Preface		ix
Contents		xi
List of Figures		xvii
List o	f Tables	xix
Nome	nclature	XX
Chapt	er 1. Introduction	1
1.1	Importance of Process Control	1
1.2	Challenges in Controller Design	1
1.3	Importance of Process Modeling and Identification in Control	2
1.3.1	Desirable Characteristics of Process Model	3
1.3.2	Classification of Process Models	4
1.4	Classification of Variables from the Process Control Perspective	9
1.5	Multivariable Process Control	10
1.5.1	Degrees of Freedom Analysis	11
1.6	Proportional Integral Derivative (PID) Feedback Control	12
1.7	PID Controller Design Methods	13
1.8	Computer Simulation	15
1.8.1	Software Platforms	15
1.8.2	Basic Types of Engineering Problems	16
1.9	General Objectives of the Present Work	17

Chapt	Chapter 2. Literature Review	
2.1	Introduction	18
2.2	Control of Multiple Input Multiple Output (MIMO) Processes	18
2.3	Control of Single Input Single Output (SISO) Stable Processes	19
2.4 Control of Single Input Single Output (SISO) Unstable Processes		20
2.5	Specific Objectives of the Present Work	30
Chapt	er 3. PID Controller Design Techniques	31
3.1	Conventional PID Controller Design Techniques	31
3.1.1	Ziegler-Nichols Closed loop Method	31
3.1.2	Tyreus-Luyben Closed loop Method	32
3.1.3	Ziegler-Nichols Open loop Method	33
3.1.4	Cohen-Coon Open loop Method	33
3.2	Internal Model Control (IMC) based Controller Design Techniques	35
3.2.1	IMC based PID Controller Design for First Order Stable Process	42
3.2.2	IMC based PID Controller Deign for Second Order Stable Process	43
3.2.3	IMC based PID Controller Deign for	
	First Order Plus Dead Time Stable Process	45
3.2.4	IMC based PID Controller Deign for First Order Unstable Process	46
3.2.5	IMC based PID Controller Deign for First Order Unstable Process	
	(RHP pole and Numerator dynamics)	48
3.3	Process Models for Controller Design	50
3.3.1	Linearized State Space Model (Time domain)	52
3.3.2	Transfer Function Model (Laplace domain)	55
3.4	Process Identification	58
3.4.1	Identification from Open loop Step Response Experimental Data	58
3.4.2	Identification from Steady State Input-Output Experimental Data	60

Chapt	er 4. Modeling, Identification and IMC based PID Control of	
Two I	nput Two Output Non-minimum Phase Nonlinear Process	62
4.1.	Introduction	62
4.1.1	Experimental Quadruple Tank Process (QTP)	62
4.2	Mathematical Model of Quadruple Tank Process (QTP)	67
4.2.1	Assumptions	68
4.2.2	Process Operating Conditions:	69
4.2.3	Unsteady State Mass balances	69
4.2.4	Steady State Solution	70
4.3	Linearized State Space Model of the Quadruple-Tank Process (QTP)	70
4.3.1	Degrees of Freedom Analysis	73
4.3.2	Classification of Variables	74
4.4	Transfer function Model of Quadruple-Tank Process (QTP)	76
4.5	Transmission Zeros of Quadruple-Tank Process (QTP)	77
4.6	Identification of Quadruple-Tank Process (QTP)	81
4.6.1	Open loop Experiments (Pure Capacity Mode)	83
4.6.1.	1 Experimental Procedure	83
4.6.1.2	2 Estimation of Linear Velocity	85
4.6.1.3	3 Estimation of Split Fractions	86
4.6.2	Open loop Experiments (Resistance Mode)	90
4.6.2.2	1 Experimental Procedure	90
4.6.2.2	2 Estimation of Nonlinear Flow Resistances	92
4.6.2.3	3 Estimation of Time Constant and Steady State Gain	95
4.7	Multivariable Process Transfer Function Matrix	97
4.7.1	Transmission Zeros	98
4.7.2	Control loop Interactions	98
4.7.2.	Relative Gain Array (RGA) Analysis	98

4.8	Closed loop Response of Quadruple Tank Process (QTP) with interactions	100
4.9	Design of Inverted Decoupling Controller	101
4.10	Closed loop Response of Quadruple Tank Process (QTP)	
	with Inverted Decoupling Controllers	102
4.11	IMC based PID Controller Design for the	
	Decoupled Quadruple Tank Process	104
4.12	Closed loop Response of IMC based PID Decoupling Controller	105
4.13	Comparison with Open Literature	106
4.14	Conclusion	108
Chapte	er 5. Modeling, Identification and IMC based PID Control of	
Single	Input Single Output Stable Nonlinear Process	109
5.1.	Introduction	109
5.2	Experimental Annular Flow Conical Tank Liquid Level	
	Nonlinear Process	109
5.2.1	Process Description	110
5.3	Mathematical Modeling of Annular Flow Conical Tank Process	112
5.3.1	Process Variables and Parameters	112
5.3.2	Unsteady State Mass balances	113
5.3.3	Linearized State Space Model and Transfer Function Model	116
5.4	Process Identification	118
5.4.1	Identification from Open loop Steady State Experimental Data	118
5.4.1.1	Experimental Procedure	119
5.4.1.2	Estimation of Nonlinear Flow Resistance	121
5.4.1.3	Estimation of Steady State Gain and Time Constant	122
5.4.2	Identification from Open loop Step response Experimental Data	125
5.5	Controller Design	126
5.5.1	Controller Design based on Cohen and Coon Method	126

5.5.2	IMC based PID Controller Design	126
5.6	Closed Loop Response	127
5.7	Conclusion	129
Chapte	er 6. Modeling and IMC based PID Control of	
	Single Input Single Output Unstable Nonlinear Process	130
6.1.	Introduction	130
6.2	Continuous Bioreactor	131
6.2.1	Mathematical Modeling of the Continuous Bioreactor	132
6.2.1.1	Unsteady State Mass Balances	132
6.2.1.2	2 Rate Equations	134
6.2.1.3	3 Steady State Solution of the Continuous Bioreactor	135
6.2.1.4	Linearized State Space Model of the Continuous Bioreactor	137
6.2.1.5	5 Stability Analysis of the Continuous Bioreactor	138
6.2.1.6	5 Degrees of Freedom Analysis of the Continuous Bioreactor	140
6.2.1.7	7 Transfer Function Model of the Continuous Bioreactor	141
6.2.2	IMC based PI Controller Design for the Continuous Bioreactor	141
6.2.3	Closed loop Response of the IMC based PI Controller	142
6.2.4	Conclusion	143
6.3	Non-Adiabatic Jacketed CSTR	144
6.3.1	Mathematical Model of the Non-adiabatic Jacketed CSTR	144
6.3.1.1	1. Unsteady State Mass and Energy Balances	144
6.3.1.2	2 Steady State Solution of the Non-adiabatic Jacketed CSTR	145
6.3.1.3	3 Linearized State Space Model of the Non-adiabatic Jacketed CSTR	146
6.3.1.4	4 Stability Analysis of the Non-adiabatic Jacketed CSTR	148
6.3.1.6	5 Degrees of Freedom Analysis	149
6.3.1.7	7 Transfer Function Model of the Non-adiabatic Jacketed CSTR	150
6.3.2	IMC based PID Controller Design for the Non-adiabatic Jacketed CSTR	152

6.3.3	Closed loop Response of the IMC based PI Controller	153
6.3.4	Conclusion	154
Chapte	Chapter 7. Summary and Scope of Future Work	
7.1	Summary of the Thesis	155
7.2.	Scope of Future Work	157
References		158
Publications		172
Appendix A. Numerical Techniques for the Solution of		
	Nonlinear Algebraic Equations	173
Appen	Appendix B. Linear Regression	
Appen	Appendix C. Tridiagonal Matrix Algorithm	

List of Figures

FIGURE 1.1	IMPORTANCE OF PROCESS MODELING AND IDENTIFICATION IN CONTROL	8
FIGURE 1.2	CLASSIFICATION OF VARIABLES FROM THE CONTROL PERSPECTIVE	10
FIGURE 1.3	MULTIVARIABLE PROCESS CONTROL	12
FIGURE 1.4	CLOSED LOOP BLOCK DIAGRAM OF A PID FEEDBACK CONTROL SYSTEM	13
FIGURE 1.5	BASIC TYPES OF ENGINEERING PROBLEMS	17
FIGURE 3.1	BLOCK DIAGRAM OF OPEN LOOP MODEL BASED CONTROLLER	38
FIGURE 3. 2	CLOSED LOOP MODEL BASED CONTROLLER	39
FIGURE 3. 3	CLOSED LOOP BLOCK DIAGRAM OF IMC BASED FEEDBACK	40
	CONTROLLER	
FIGURE 3.4	CLOSED LOOP BLOCK DIAGRAM OF IMC BASED PID	41
	CONTROLLER	
FIGURE 3.5	BLOCK DIAGRAM OF CLOSED LOOP TRANSFER FUNCTIONS	42
FIGURE 3. 6`	BLOCK DIAGRAM OF SINGLE INPUT SINGLE OUTPUT (SISO)	56
	PROCESS	
FIGURE 3.7	BLOCK DIAGRAM OF TWO INPUT TWO OUTPUT (TITO) PROCESS	57
FIGURE 4.1	EXPERIMENTAL SETUP OF THE QUADRUPLE TANK PROCESS	64
	(QTP)	
FIGURE 4.2	SCHEMATIC OF THE QUADRUPLE TANK PROCESS (QTP)	65
FIGURE 4.3	PROCESS VARIABLES AND SYSTEM PARAMETERS IN THE	67
	QUADRUPLE TANK PROCESS (QTP)	
FIGURE 4.4	OPEN LOOP RESPONSE OF QUADRUPEL TANK PROCESS (PURE CAPACITY MODE)	87
FIGURE 4.5	ESTIMATION OF LINEAR VELOCITY OF TANK 1	87
FIGURE 4.6	ESTIMATION OF LINEAR VELOCITY OF TANK 2	88
FIGURE 4.7	ESTIMATION OF LINEAR VELOCITY OF TANK 3	88
FIGURE 4.8	ESTIMATION OF LINEAR VELOCITY OF TANK 4	89
FIGURE 4.9	OPEN LOOP STEP RESPONSE OF LIQUID LEVEL IN TANK 1 AND TANK 2	92
FIGURE 4.10	STEADY STATE INPUT-OUTPUT CURVE FOR TANK 1	93
FIGURE 4.11	STEADY STATE INPUT-OUTPUT CURVE FOR TANK 2	93
FIGURE 4.12	STEADY STATE INPUT-OUTPUT CURVE FOR TANK 3	94
FIGURE 4.13	STEADY STATE INPUT-OUTPUT CURVE FOR TANK 4	94
FIGURE 4.14	CLOSED LOOP RESPONSE OF CONVENTIONAL CONTROLLER	101
	(WITH INTERACTIONS)	
FIGURE 4.15	CLOSED LOOP BLOCK DIAGRAM WITH INVERTED DECOUPLING	102
	CONTROLLERS	
FIGURE 4.16	CLOSED LOOP RESPONSE OF CONVENTIONAL CONTROLLER	103
	(WITH DECOUPLERS)	
FIGURE 4.17	CLOSED LOOP RESPONSE OF INVERTED DECOUPLING IMC-PID	105
	CONTROLLERS	
FIGURE 4.18	COMPARATIVE PERFORMANCE OF IMC-PID DECOUPLING	107
	CONTROLLERS	
FIGURE 5.1	EXPERIMENTAL SETUP OF CONICAL TANK PROCESS	111
FIGURE 5.2	SCHEMATIC DIAGRAM OF CONICAL TANK PROCESS	111
FIGURE 5.3	PROCESS MODEL OF CONICAL TANK LIQUID LEVEL PROCESS	112
FIGURE 5.4	RELATIONSHIP BETWEEN VOLUMETRIC FLOWRATE AND CONTROLLER OUTPUT	119

FIGURE 5.5	RELATIONSHIP BETWEEN VOLUMETRIC FLOWRATE AND	120
	PNEUMATIC VALVE STEM PRESSURE	
FIGURE 5.6	RELATIONSHIP BETWEEN PNEUMATIC VALVE STEM PRESSURE	121
	AND CONTROLLER OUTPUT	
FIGURE 5.7	ESTIMATION OF NONLINEAR FLOW RESISTANCE	122
FIGURE 5.8	VARIATION OF STEADY STATE GAIN WITH RESPECT TO HEIGHT	124
FIGURE 5.9	VARIATION OF TIME CONSTANT WITH RESPECT TO HEIGHT	124
FIGURE 5.10	OPEN LOOP STEP RESPONSE OF LIQUID LEVEL IN CONICAL	125
	TANK PROCESS	
FIGURE 5.11	CLOSED LOOP BLOCK DIAGRAM OF IMC BASED PID	127
	CONTROLLER	
FIGURE 5.12	COMPARISON OF EXPERIMENTAL CLOSED LOOP RESPONSES	129
FIGURE 6.1	SCHEMATIC OF CONTINUOUS BIOREACTOR	131
FIGURE 6.2	COMPARIOSN OF THE MONOD AND THE SUBSTRATE	135
	INHIBITION (SI) MODELS	
FIGURE 6.3	TUNING OF IMC BASED PI CONTROLLER FOR CONTINUOUS	142
	BIOREACTOR	
FIGURE 6.4	CLOSED LOOP RESPONSE OF BIOREACTOR WITH IMC BASED PID	143
	CONTROLLER	
FIGURE 6.5	SCHEMATIC OF THE NON-ADIABATIC JACKETED CSTR	144
FIGURE 6.6	IMC BASED PID CONTROLLER TUNING OF THE NON-ADIABATIC	152
	JACKETED CSTR	
FIGURE 6.7	CLOSED LOOP RESPONSE OF IMC BASED PID CONTROLLER	153

List of Tables

TABLE 1.1	PID CONTROLLER DESIGN METHODS	14
TABLE 1.2	CONTROLLER PERFORMANCE CRITERIA (QUANTITATIVE PERFORMANCE INDEX)	14
TABLE 3.1	PID CONTROLLER PARAMETERS: ZIEGLER-NICHOLS CLOSED LOOP METHOD	32
TABLE 3.2	PID CONTROLLER PARAMETERS: TYREUS-LUYBEN	32
TABLE 3.3	PID CONTROLLER TUNING PARAMETERS BASED ON ZIEGLER-NICHOLS OPEN LOOP METHOD	33
TABLE 3.4	PID CONTROLLER TUNING PARAMETERS SUGGESTED BY COHEN AND COON OPEN LOOP METHOD	34
TABLE 3.5	DIMENSIONALITY OF STATE SPACE AND TRANSFER FUNCTION MODELS	57
TABLE 4.1	TECHNICAL SPECIFICATIONS OF THE EXPERIMENTAL QUADRUPLE TANK PROCESS	66
TABLE 4.2	PROCESS VARIABLES AND SYSTEM PARAMETERS IN QTP	68
TABLE 4.3	CLASSIFICATION OF PROCESS VARIABLES AND SYSTEM PARAMETERS IN QTP	74
TABLE 4.4	DESIGN PARAMETERS OF QUADRUPLE-TANK PROCESS EXPERIMENTAL SETUP	82
TABLE 4.5	OPEN LOOP EXPERIMENT 1 (PURELY CAPACITIVE MODE)	84
TABLE 4.6	OPEN LOOP EXPERIMENT 2 (PURELY CAPACITIVE MODE)	85
TABLE 4.7	ESTIMATION OF SPLIT FRACTIONS	89
TABLE 4.8	STEADY STATE EXPERIMENTAL DATA OF QUADRUPLE TANK PROCESS	91
TABLE 4.9	ESTIMATION OF NONLINEAR FLOW RESISTANCE	95
TABLE 4. 10	ESTIMATION OF TIME CONSTANTS CORRESPONDING TO DIFFERENT STEADY STATES	96
TABLE 4. 11	ESTIMATION OF STEADY STATE GAIN CORRESPONDING TO DIFFERENT STEADY STATES	97
TABLE 4. 12	QUANTITATIVE PERFORMANCE INDICES (QPI) FOR CONVENTIONAL CONTROLLER	104
TABLE 4. 13	QPI FOR IMC BASED PID DECOUPLING CONTROLLER	106
TABLE 4. 14	QUANTITATIVE PERFORMANCE INDICES (QPI) FOR COMPARATIVE STUDY	108
TABLE 5.1	SPECIFICATION OF ANNULAR FLOW CONICAL TANK LIQUID LEVEL SETUP	110
TABLE 5.2	ESTIMATION OF PROCESS PARAMETERS FROM EXPERIMENTAL STEADY STATE DATA.	123
TABLE 5.3	IMC BASED PID CONTROLLER PARAMETERS CORRESPONDING TO DIFFERENT STEADY STATES	126
TABLE 5.4	QUANTITATIVE PERFORMANCE INDICES FOR IMC BASED PID CONTROLLER.	128
TABLE 6.1	PARAMETERS AND VARIABLES IN CONTINUOUS BIOREACTOR	132
TABLE 6.2	PARAMETERS OF THE SUBSTRATE INHIBITION MODEL AND THE MONOD MODEL	135
TABLE 6.3	OPERATING CONDITIONS OF THE CONTINUOUS BIOREACTOR	136
TABLE 6.4	STABILITY ANALYSIS OF STEADY STATES IN CONTINUOUS BIOREACTOR	140
TABLE 6.5	OPERATING CONDITIONS AND DESIGN PARAMETERS OF THE CSTR	145
TABLE 6.6	MULTIPLE STEADY STATES IN THE NON-ADIABATIC JACKETED CSTR	146
TABLE 6.7	STEADY STATE MULTIPLICITY AND STABILITY ANALYSIS OF THE CSTR	148
TABLE 6.8	CLASSIFICATION OF VARIABLES AND PARAMETERS IN THE NON- ADIABATIC JACKETED CSTR	149