

TABLE OF CONTENTS

CHAPTER NO.	TITLE	PAGE NO.
	ABSTRACT	iii
	LIST OF TABLES	ix
	LIST OF FIGURES	x
	LIST OF SYMBOLS AND ABBREVIATIONS	xviii
1	INTRODUCTION	1
	1.1 INTRODUCTION	1
	1.2 OBJECTIVE OF THE THESIS	2
	1.3 ORGANISATION OF THE THESIS	3
2	LITERATURE REVIEW	4
	2.1 MODELING	4
	2.2 STATE AND PARAMETER ESTIMATION	7
	2.3 MODEL PREDICTIVE CONTROL	11
3	DESIGN OF OBSERVER AND OBSERVER BASED NMPC FORMULATION	18
	3.1 INTRODUCTION	18
	3.2 UNCONSTRAINED OBSERVER DESIGN	18
	3.3 EXTENDED KALMAN FILTER (EKF)	21
	3.4 DESIGN OF FUZZY OBSERVER	24
	3.4.1 Fuzzy Dynamic Model	24
	3.4.2 Fuzzy Kalman Filter (FKF)	26

CHAPTER NO.	TITLE	PAGE NO.
3.5	NONLINEAR MODEL PREDICTIVE CONTROLLER (NMPC)	27
3.5.1	NMPC formulation using T-S fuzzy dynamic model	27
3.5.2	NMPC formulation using Fuzzy Kalman Filter (FKF)	30
3.5.3	NMPC formulation using Augmented State Fuzzy Kalman Filter (ASFKF)	33
4	IMPLEMENTATION OF OBSERVER DESIGN TO CSTRs	37
4.1	INTRODUCTION	37
4.2	PROCESS DESCRIPTION	37
4.2.1	Continuous Stirred Tank Reactor (CSTR-I)	37
4.2.2	Continuous Stirred Tank Reactor (CSTR-II)	40
4.2.3	Multiple steady state characteristics (CSTR-II)	42
4.3	OBSERVER FOR CSTR-I	44
4.3.1	Fuzzy model for CSTR-I process	47
4.3.2	FKF for CSTR-I process	51
4.3.3	Augmented-state fuzzy Kalman filter for CSTR-I process	52
4.3.3.1	Input disturbance: state estimation in the presence of a step change in the feed temperature	53

CHAPTER NO.	TITLE	PAGE NO.
	4.3.3.2 Output disturbance: state estimation in the presence of a bias in the temperature sensor	55
4.4	OBSERVER FOR CSTR-II	58
	4.4.1 FKF for CSTR-II process	58
4.5	COMPARISON OF FUZZY KALMAN FILTER AND EXTENDED KALMAN FILTER	63
5	OBSERVER BASED NMPC FOR CSTRs	59
5.1	INTRODUCTION	59
5.2	CLOSED-LOOP SIMULATION STUDIES OF CSTR-I	59
	5.2.1 Servo response of CSTR-I with fuzzy dynamic model based NMPC	60
	5.2.2 Servo and regulatory responses of CSTR-I with fuzzy dynamic model based NMPC	62
	5.2.3 Servo response of CSTR-I with FKF based NMPC	63
	5.2.4 Regulatory response of CSTR-I with FKF based NMPC	66
	5.2.5 Regulatory response of CSTR-I with ASFKF based NMPC	69
	5.2.6 Servo response of CSTR-I with FKF based NMPC (Inferential Measurement)	71

CHAPTER NO.	TITLE	PAGE NO.
	5.2.7 Regulatory response of CSTR-I with FKF and ASFKF based NMPC schemes (Inferential Measurement)	75
5.3	CLOSED-LOOP SIMULATION STUDIES OF CSTR-II	79
5.3.1	Servo response of CSTR-II with FKF based NMPC	80
5.3.2	Regulatory response of CSTR-II with FKF and ASFKF based NMPC schemes	83
6	SUMMARY AND CONCLUSION	88
6.1	CONCLUSION	88
6.2	SCOPE FOR FUTURE WORK	89
	REFERENCES	90
	LIST OF PUBLICATIONS	95
	VITAE	96

LIST OF TABLES

TABLE NO.	TITLE	PAGE NO.
4.1	Steady state operating data of CSTR-I	38
4.2	Steady state operating data of CSTR-II	41
4.3	Eigen values, damping factor and undamped natural frequency at different operating points	44
4.4	Estimation error for 25 Monte-Carlo simulations	66
5.1	ISE values of CSTR-I with fuzzy dynamic model based NMPC for various values of Prediction Horizon	70
5.2	ISE values of CSTR-I with FKF based NMPC for various values of Prediction Horizon	75
5.3	ISE values of CSTR-I with FKF based NMPC (Inferential Control Case) for various values of Prediction Horizon	84
5.4	ISE values of CSTR-II with FKF based NMPC for various values of Prediction Horizon	94

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE NO.
3.1	Block diagram of NMPC Control Scheme	28
3.2	Basic concept of NMPC	30
4.1	CSTR-I	39
4.2	CSTR-II	41
4.3	Reactor temperature vs. Jacket temperature of CSTR-II	43
4.4	Variation in coolant flow rate of CSTR-I	45
4.5	Comparison of the open loop responses of rigorous model and linear model of CSTR-I - Reactor Concentration	46
4.6	Comparison of the open loop responses of rigorous model and linear model of CSTR-I - Reactor Temperature	46
4.7	Membership function	48
4.8	Comparison of the open loop responses of rigorous model and fuzzy model of CSTR-I - Reactor Concentration	50
4.9	Comparison of the open loop responses of rigorous model and fuzzy model of CSTR-I - Reactor Temperature	50
4.10	Evolution of true and estimated reactor concentration of CSTR-I with FKF	51
4.11	Evolution of true and estimated reactor temperature of CSTR-I with FKF	52

FIGURE NO.	TITLE	PAGE NO.
4.12	Evolution of true and estimated reactor concentration of CSTR-I with ASFKF (Input Disturbance)	54
4.13	Evolution of true and estimated reactor temperature of CSTR-I with ASFKF (Input Disturbance)	54
4.14	Evolution of true and estimated feed temperature of CSTR-I with ASFKF	55
4.15	Evolution of true and estimated reactor concentration of CSTR-I with ASFKF (Output Disturbance)	56
4.16	Evolution of true and estimated reactor temperature of CSTR-I with ASFKF (Output Disturbance)	57
4.17	Evolution of sensor bias estimates of CSTR-I	57
4.18	Membership function of CSTR-II	58
4.19	Variation in jacket temperature of CSTR-II	61
4.20	Evolution of true and estimated reactor concentration of CSTR-II with FKF (initial state of the process and estimator being at stable steady state)	61
4.21	Evolution of true and estimated reactor temperature of CSTR-II with FKF (initial state of the process and estimator being at stable steady state)	62
4.22	Evolution of true and estimated reactor concentration of CSTR-II with FKF (initial state of the process and estimator being at unstable steady state)	62

FIGURE NO.	TITLE	PAGE NO.
4.23	Evolution of true and estimated reactor temperature of CSTR-II with FKF (initial state of the process and estimator being at unstable steady state)	63
4.24	Evolution of true and estimated reactor concentration of CSTR-I with FKF and EKF	65
4.25	Evolution of true and estimated reactor temperature of CSTR-I with FKF and EKF	65
4.26	Histogram of CSTR-I computation time per sampling instant - FKF	67
4.27	Histogram of CSTR-I computation time per sampling instant - EKF	67
5.1	Servo response of CSTR-I with fuzzy dynamic model based NMPC (a) Process output (b) Controller output	69
5.2	Servo response of CSTR-I with fuzzy dynamic model based NMPC for various values of prediction horizon (a) Process output (b) Controller output	70
5.3	Servo and regulatory responses of CSTR-I with fuzzy dynamic model based NMPC (a) Process output (b) Controller output	71
5.4	Variation in feed temperature of CSTR-I	72
5.5	Servo response of CSTR-I with FKF based NMPC (a) Process output (b) Controller output	73

FIGURE NO.	TITLE	PAGE NO.
5.6	Evolution of true and estimated states of reactor concentration of CSTR-I with FKF based NMPC	74
5.7	Evolution of true and estimated states of reactor temperature of CSTR-I with FKF based NMPC	74
5.8	Servo response of CSTR-I with FKF based NMPC for various values of prediction horizon (a) Process output (b) Controller output	75
5.9	Regulatory response of CSTR-I with FKF based NMPC (a) Process output (b) Controller output	76
5.10	Evolution of true and estimated states of reactor concentration of CSTR-I in the presence of step change in feed temperature (FKF based NMPC)	77
5.11	Evolution of true and estimated states of reactor temperature of CSTR-I in the presence of step change in feed temperature (FKF based NMPC)	77
5.12	Variation in feed temperature of CSTR-I	78
5.13	Regulatory response of CSTR-I with ASFKF based NMPC (a) Process output (b) Controller output	79

FIGURE NO.	TITLE	PAGE NO.
5.14	Evolution of true and estimated states of reactor concentration of CSTR-I in the presence of step change in feed temperature (ASFKF based NMPC)	79
5.15	Evolution of true and estimated states of reactor temperature of CSTR-I in presence of step change in feed temperature (ASFKF based NMPC)	80
5.16	Evolution of true and estimated feed temperatures of CSTR-I (ASFKF based NMPC)	80
5.17	Servo response of CSTR-I with FKF based NMPC (Inferential Control Case) Process output	82
5.18	Evolution of true and estimated states of reactor concentration of CSTR-I with FKF based NMPC (Inferential Control Case - Servo Problem)	82
5.19	Evolution of true and estimated state variables with LMPC (Inferential Control Case-Servo Problem)	83
5.20	Servo response of CSTR-I for various values of prediction horizon with FKF based NMPC (Inferential Control Case) (a) Process output (b) Controller output	83

FIGURE NO.	TITLE	PAGE NO.
5.21	Regulatory response of CSTR-I with FKF based NMPC (Inferential Control Case) (a) Process output (b) Controller output	85
5.22	Evolution of true and estimated states of reactor concentration of CSTR-I in the presence of step change in feed temperature (FKF based NMPC - Inferential Control Case)	85
5.23	Evolution of true and estimated states of reactor temperature of CSTR-I in the presence of step change in feed temperature (FKF based NMPC -Inferential Control Case)	86
5.24	Servo-Regulatory response of CSTR with FKF based NMPC (with and without Move Suppressions) (a) Process output (b) Controller output	86
5.25	Regulatory response of CSTR-I with ASFKF based NMPC (Inferential Control Case) (a) Process output (b) Controller output	87
5.26	Evolution of true and estimated states of reactor concentration of CSTR-I in the presence of step change in feed temperature (ASFKF based NMPC-Inferential Control Case)	88

FIGURE NO.	TITLE	PAGE NO.
5.27	Evolution of true and estimated states of reactor temperature of CSTR-I in the presence of step change in feed temperature (ASFKF based NMPC-Inferential Control Case)	88
5.28	Evolution of true and estimated feed temperatures of CSTR-I (ASFKF based NMPC - Inferential Control Case)	89
5.29	Servo response of CSTR-II with FKF based NMPC (a) Process output (b) Controller output	92
5.30	Evolution of true and estimated states of reactor concentration of CSTR-II with FKF based NMPC	92
5.31	Evolution of true and estimated states of reactor temperature of CSTR-II with FKF based NMPC	93
5.32	Servo response of CSTR-II with FKF based NMPC for various values of prediction horizon (a) Process output (b) Controller output	93
5.33	Regulatory response of CSTR-II with FKF based NMPC (a) Process output (b) Controller output	95
5.34	Evolution of true and estimated states of reactor concentration of CSTR-II in the presence of step change in feed temperature (FKF based NMPC)	95

FIGURE NO.	TITLE	PAGE NO.
5.35	Evolution of true and estimated states of reactor temperature of CSTR-II in the presence of step change in feed temperature (FKF based NMPC)	96
5.36	Variation in feed temperature of CSTR-II	96
5.37	Regulatory response of CSTR-II with ASFKF based NMPC (a) Process output (b) Controller output	97
5.38	Evolution of true and estimated states of reactor concentration of CSTR-II in the presence of step change in feed temperature (ASFKF based NMPC)	97
5.39	Evolution of true and estimated states of reactor temperature of CSTR-II in the presence of step change in feed temperature (ASFKF based NMPC)	98
5.40	Evolution of true and estimated feed temperatures of CSTR-II (ASFKF based NMPC)	98

LIST OF SYMBOLS AND ABBREVIATIONS

Q_β, Q_η	Covariance matrices
x	True state variable
$\hat{x}(k/k)$	Updated state estimates
$\hat{x}(k/k-1)$	Predicted state estimates
$P(k/k)$	Updated error covariance matrix
$P(k/k-1)$	Predicted error covariance matrix
$y(k)$	Measured variables
$u(k)$	Process inputs
$v(k)$	Measurement errors
$w(k)$	State noise vectors
A	State transition matrix (continuous domain)
B	Input matrix (continuous domain)
C	Measurement matrix
F	Jacobian matrix
$h_i(z(k))$	Grade of membership
$K_i(k)$	Kalman gain matrix
$P_i(k/k-1)$	Error covariance matrix of predicted state estimate
$P_i(k/k)$	Error covariance matrix of updated state estimate
β and η	Additional linear states
N_p	Prediction horizon
N_c	Control horizon
$y_m(k)$	Measured output
W_E	Error weighting matrix
W_U	Input move weight matrix

CSTR-I

C_A	Concentration (mol/L)
T	Temperature (K)
Q	State noise covariance matrices
R	Measurement noise covariance matrices
q_c	Coolant flow rate (L/min)
q	Feed flow rate (L/min)
C_{A0}	Feed concentration (mol/L)
T_0	Feed temperature (K)
T_{c0}	Inlet coolant temperature (K)
V	CSTR volume (L)
hA	Heat transfer term (cal/(min.K))
k_0	Reaction rate constant (min^{-1})
E/R	Activation energy term (K)
$-\Delta H$	Heat of reaction (cal/mol)
ρ, ρ_c	Liquid density (g/L)
C_p, C_{pc}	Specific heats (g.K)

CSTR-II

A	Area for heat exchanger (m^2)
C_A	Concentration of A in reactor (kgmol/m^3)
C_{Af}	Concentration of A in feed stream (kgmol/m^3)
C_p	Heat capacity (energy/mass * temperature)
F	Volumetric flow rate (volume/time)
k_0	Pre-exponential factor (time^{-1})
R	Ideal gas constant (energy/ mol * temperature)
r	Rate of reaction per unit volume (mol/volume * time)
t	Time (hrs)
T	Reactor temperature (Deg.k)

T_f	Feed temperature (Deg.k)
T_j	Jacket temperature (Deg.k)
T_{ref}	Reference temperature (Deg.k)
U	Overall heat transfer coefficient (energy/ (time * area * temperature))
V	Reactor volume (m^3)
ΔE	Activation energy (energy/mol)
ΔH	Heat of reaction (energy/mol)
ρ	Density (mass/volume)

Greek Letter

Φ	State transition matrix (Discrete domain)
Γ	Input coupling matrix (Discrete domain)
Υ	Disturbance coupling matrix
μ	Mean of estimation error
σ	Standard deviation of estimation error
η	Output disturbance vector
β	Input disturbance vector

Abbreviations

ASFKF	Augmented State Fuzzy Kalman Filter
CSTR	Continuous Stirred Tank Reactor
DMC	Dynamic Matrix Control
EDMC	Extended Dynamic Matrix Control
EKF	Extended Kalman Filter
FKF	Fuzzy Kalman Filter
LMPC	Linear Model Predictive Control

MBPC	Model Based Predictive Control
MIMO	Multi Input Multi Output
MPC	Model Predictive Controller
NARX	Nonlinear Auto Regressive eXogenous
NMPC	Nonlinear Model Predictive Controller
T-S	Takagi-Sugeno