

Contents

Preface	ix
List of Figures	xi
List of Tables	xvii
1 Introduction	1
1.1 Motivation	1
1.2 Examples of Transport-Reaction Processes	2
1.2.1 A plug-flow reactor	2
1.2.2 Rapid thermal chemical vapor deposition	3
1.3 Background on Control of PDE Systems	5
1.4 Objectives and Organization of the Book	8
2 Feedback Control of Hyperbolic PDE Systems	11
2.1 Introduction	11
2.2 First-Order Hyperbolic PDE Systems	12
2.2.1 Preliminaries	12
2.2.2 Specification of the control problem	13
2.2.3 Review of system-theoretic properties	16
2.2.4 Methodology for control	18
2.3 Characteristic Index	19
2.4 State Feedback Control	21
2.4.1 Linear systems	21
2.4.2 Quasi-linear systems	24
2.5 Closed-Loop Stability	25
2.6 Output Feedback Control	27
2.6.1 Linear systems	28
2.6.2 Quasi-linear systems	30
2.7 Application to a Nonisothermal Plug-Flow Reactor	31
2.7.1 Process description and modeling	31
2.7.2 Control problem formulation—Controller synthesis	33
2.7.3 Evaluation of controller performance	38
2.7.4 A practical implementation issue	41
2.8 Conclusions	45
3 Robust Control of Hyperbolic PDE Systems	47
3.1 Introduction	47
3.2 Preliminaries	48
3.3 Uncertainty Decoupling	50

3.4 Robust Control: Uncertain Variables	53
3.5 Two-Time-Scale Hyperbolic PDE Systems	56
3.5.1 Two-time-scale decomposition	57
3.5.2 Stability results	58
3.6 Robustness with Respect to Unmodeled Dynamics	60
3.6.1 Robustness of uncertainty decoupling to unmodeled dynamics	60
3.6.2 Robust control: uncertain variables and unmodeled dynamics	61
3.7 Application to a Fixed-Bed Reactor	63
3.8 Conclusions	68
4 Feedback Control of Parabolic PDE Systems	71
4.1 Introduction	71
4.2 Preliminaries	72
4.2.1 Description of parabolic PDE systems	72
4.2.2 Formulation of parabolic PDE system as infinite- dimensional system—Eigenvalue problem	73
4.3 Examples of Processes Modeled by Nonlinear Parabolic PDEs	75
4.3.1 Catalytic rod	75
4.3.2 Nonisothermal tubular reactor with recycle	77
4.4 Galerkin's Method	81
4.5 Accuracy of ODE System Obtained From Galerkin's Method	82
4.6 Construction of ODE Systems of Desired Accuracy via AIMS	85
4.7 Nonlinear Output Feedback Control	87
4.7.1 A general result	87
4.7.2 Controller synthesis	90
4.8 Applications	92
4.8.1 Catalytic rod	92
4.8.2 Nonisothermal tubular reactor with recycle	94
4.9 Conclusions	97
5 Robust Control of Parabolic PDE Systems	99
5.1 Introduction	99
5.2 Preliminaries	100
5.2.1 Parabolic PDE systems with uncertainty	100
5.2.2 Illustrative example: catalytic rod with uncertainty	101
5.3 Robust State Feedback Control of Parabolic PDE Systems	103
5.3.1 Problem formulation— Finite-dimensional approximation	103
5.3.2 Robust state feedback controller synthesis	105

5.3.3 Improving uncertainty attenuation using approximate inertial manifolds	109
5.4 Robust Output Feedback Controller Synthesis	113
5.5 Application to a Catalytic Rod with Uncertainty	115
5.6 Conclusions	121
6 Nonlinear and Robust Control of Parabolic PDE Systems with Time-Dependent Spatial Domains	123
6.1 Introduction	123
6.2 Preliminaries	124
6.2.1 Parabolic PDE systems with time-dependent spatial domains	124
6.2.2 Formulation of the parabolic PDE system in Hilbert space	126
6.2.3 Singular perturbation formulation	127
6.2.4 Illustrative example: Catalytic rod with moving boundary	128
6.3 Nonlinear Model Reduction	130
6.4 Nonlinear Output Feedback Control	134
6.5 Application to a Catalytic Rod with Moving Boundary	137
6.6 Robust Control of Parabolic PDEs with Time-Dependent Spatial Domains	141
6.6.1 Preliminaries	141
6.6.2 Robust nonlinear output feedback controller synthesis	143
6.7 Application to a Catalytic Rod with Moving Boundary and Uncertainty	147
6.8 Conclusions	150
7 Case Studies	153
7.1 Nonlinear Control of Rapid Thermal Chemical Vapor Deposition	153
7.1.1 Introduction	153
7.1.2 Modeling of RTCVD process	154
7.1.3 Nonlinear controller synthesis— Closed-loop simulations	157
7.2 Nonlinear Control of Czochralski Crystal Growth	164
7.2.1 Introduction	164
7.2.2 Czochralski crystal growth process description and modeling	165
7.2.3 Control-relevant analysis of the Czochralski crystal growth	170
7.2.4 Nonlinear controller synthesis— Closed-loop simulations	180
7.3 Conclusions	192

Appendix A: Proofs of Chapter 2	193
Appendix B: Proofs of Chapter 3	201
Appendix C: Proofs of Chapter 4	211
Appendix D: Proofs of Chapter 5	217
Appendix E: Proofs of Chapter 6	223
Appendix F: Karhunen–Loève Expansion	229
References	233
Index	247