

Contents

Abstract	iii
Acknowledgements	xi
1 Introduction	1
1.1 State of the Art	2
1.1.1 Redox Flow Batteries	2
1.1.2 All Vanadium Redox Flow Batteries (VRFB)	6
1.1.3 Vanadium/Air Redox Flow Batteries (VARFB)	9
1.1.4 Cell Designs	13
1.2 Aim of the Thesis	18
1.3 Thesis Outline	19
2 Fundamentals	23
2.1 Figures of Merit	23
2.1.1 Current and Charge	24
2.1.2 Cell Potential	28
2.1.3 Power and Energy	36
2.1.4 State of Charge	37
2.1.5 Efficiencies	39
2.2 Methods	41
2.2.1 Current Interrupt	42
2.2.2 Polarization Curves	43
2.2.3 Half Cell Potential Measurement	46
2.2.4 Electrochemical Impedance Spectroscopy	51
2.3 Design Principles for Tubular Cells	55
2.3.1 Design Requirements	55
2.3.2 Electrical Cell Resistance	62
2.3.3 Pressure Drop	66
2.3.4 Tubular Cell Concepts	70

3 Tubular All Vanadium Redox Flow Cells	75
3.1 Experimental	75
3.1.1 Test Cells	76
3.1.2 Fabrication and Material Preparation	82
3.1.3 All Vanadium Redox Flow Battery Test Rig	86
3.1.4 Test Routines	89
3.2 Results and Discussion	93
3.2.1 Liquid Permeability and Pressure Drop	93
3.2.2 Planar Reference Cell Characterization	99
3.2.3 Tubular VRFB Cell Performance	104
3.2.4 Half Cell Overpotentials	120
3.2.5 Charge/Discharge Cycling	122
3.2.6 Stability and Degradation	130
3.3 Conclusions	135
3.3.1 Tubular flow-through VRFB cells (<i>FT-VRFB</i>)	136
3.3.2 Tubular flow-by VRFB cells (<i>FB-VRFB</i>)	137
3.3.3 Degradation	140
3.3.4 Measurement Setup and Methods	140
4 Tubular Vanadium/Air Redox Flow Cells	143
4.1 Experimental	143
4.1.1 Tubular Vanadium/Air Redox Flow Cell	144
4.1.2 MEA Fabrication and Material Preparation	146
4.1.3 Vanadium/Air Redox Flow Battery Test Rig	150
4.1.4 Test Routines	152
4.2 Results and Discussion	156
4.2.1 Cell Performance	157
4.2.2 Cross-Over and OCV drop	172
4.2.3 Electrode Overpotentials	178
4.3 Conclusions	180
4.3.1 Performance Characteristics and Limitations	180
4.3.2 Cross-Over	183
4.3.3 Voltage Losses	184
4.3.4 Tubular MEA Design	186
5 Conclusions and Outlook	189
5.1 Conclusions	189
5.2 Outlook	196
Bibliography	199