

# Contents

|                                                             |           |
|-------------------------------------------------------------|-----------|
| <b>Abstract</b>                                             | <b>1</b>  |
| <b>Zusammenfassung</b>                                      | <b>3</b>  |
| <b>1 Introduction</b>                                       | <b>5</b>  |
| 1.1 Motivation . . . . .                                    | 5         |
| 1.2 Goals . . . . .                                         | 8         |
| 1.3 Outline . . . . .                                       | 9         |
| <b>2 Basics of lithium-ion cells</b>                        | <b>11</b> |
| 2.1 Charging and discharging of lithium-ion cells . . . . . | 11        |
| 2.2 Cell formats of lithium-ion cells . . . . .             | 13        |
| 2.3 Overview of lithium-ion cell components . . . . .       | 14        |
| 2.3.1 Cathode chemistries . . . . .                         | 15        |
| 2.3.2 Anode chemistries . . . . .                           | 17        |
| 2.3.3 Separator design . . . . .                            | 19        |
| 2.3.4 Electrolyte configurations . . . . .                  | 19        |
| 2.4 Heat generation in lithium-ion cells . . . . .          | 20        |
| 2.5 Thermal parameters of lithium-ion cells . . . . .       | 21        |
| 2.5.1 Thermal conductivity . . . . .                        | 21        |
| 2.5.2 Heat capacity . . . . .                               | 23        |
| 2.5.3 Thermal homogenization of lithium-ion cells . . . . . | 24        |
| 2.6 Thermal simulation of lithium-ion cells . . . . .       | 25        |
| <b>3 In-plane thermal conductivity</b>                      | <b>31</b> |
| 3.1 Background . . . . .                                    | 31        |
| 3.1.1 Existing measurement approaches . . . . .             | 31        |

|          |                                                                 |           |
|----------|-----------------------------------------------------------------|-----------|
| 3.1.2    | Available literature data . . . . .                             | 32        |
| 3.1.3    | Recorded parametric effects . . . . .                           | 34        |
| 3.1.4    | Preview . . . . .                                               | 35        |
| 3.2      | Experimental . . . . .                                          | 35        |
| 3.2.1    | Measurement setup . . . . .                                     | 36        |
| 3.2.2    | Sample cells . . . . .                                          | 38        |
| 3.2.3    | Validation and determination of measurement error . . . . .     | 39        |
| 3.3      | Results and discussion . . . . .                                | 40        |
| 3.3.1    | Effect of temperature on the in-plane thermal conductivity . .  | 41        |
| 3.3.2    | Effect of SOC on the in-plane thermal conductivity . . . . .    | 42        |
| 3.3.3    | Effect of SOH on the in-plane thermal conductivity . . . . .    | 42        |
| 3.3.4    | Analytical prediction of the in-plane thermal conductivity . .  | 44        |
| 3.4      | Summary . . . . .                                               | 46        |
| <b>4</b> | <b>Through-plane thermal conductivity</b>                       | <b>49</b> |
| 4.1      | Background . . . . .                                            | 49        |
| 4.1.1    | Existing measurement approaches . . . . .                       | 50        |
| 4.1.2    | Available literature data . . . . .                             | 51        |
| 4.1.3    | Recorded parametric effects . . . . .                           | 51        |
| 4.1.4    | Preview . . . . .                                               | 53        |
| 4.2      | Experimental . . . . .                                          | 54        |
| 4.2.1    | Measurement setup . . . . .                                     | 54        |
| 4.2.2    | Sample cells . . . . .                                          | 56        |
| 4.2.3    | Validation and determination of measurement error . . . . .     | 57        |
| 4.3      | Results and discussion . . . . .                                | 58        |
| 4.3.1    | Effect of temperature on the through-plane thermal conductivity | 58        |
| 4.3.2    | Effect of SOC on the through-plane thermal conductivity . . .   | 59        |
| 4.3.3    | Effect of SOH on the through-plane thermal conductivity . . .   | 61        |
| 4.3.4    | Analytical prediction of the through-plane thermal conductivity | 62        |
| 4.4      | Summary . . . . .                                               | 64        |
| <b>5</b> | <b>Specific heat capacity</b>                                   | <b>67</b> |
| 5.1      | Background . . . . .                                            | 67        |
| 5.1.1    | Existing measurement approaches . . . . .                       | 68        |
| 5.1.2    | Available literature data . . . . .                             | 69        |
| 5.1.3    | Recorded parametric effects . . . . .                           | 70        |

|          |                                                                  |            |
|----------|------------------------------------------------------------------|------------|
| 5.1.4    | Preview . . . . .                                                | 72         |
| 5.2      | Experimental . . . . .                                           | 72         |
| 5.2.1    | Measurement setup . . . . .                                      | 73         |
| 5.2.2    | Sample cells . . . . .                                           | 74         |
| 5.2.3    | Validation and determination of measurement error . . . . .      | 75         |
| 5.3      | Results and discussion . . . . .                                 | 76         |
| 5.3.1    | Effect of temperature on the specific heat capacity . . . . .    | 77         |
| 5.3.2    | Effect of SOC on the specific heat capacity . . . . .            | 78         |
| 5.3.3    | Effect of SOH on the specific heat capacity . . . . .            | 79         |
| 5.3.4    | Analytical prediction of the specific heat capacity . . . . .    | 81         |
| 5.4      | Summary . . . . .                                                | 83         |
| <b>6</b> | <b>Effects on the thermal simulation</b>                         | <b>85</b>  |
| 6.1      | Background . . . . .                                             | 85         |
| 6.1.1    | Existing thermal simulations and parametrization . . . . .       | 86         |
| 6.1.2    | Preview . . . . .                                                | 88         |
| 6.2      | Thermal-electrical-electrochemical model . . . . .               | 89         |
| 6.2.1    | Modeling framework . . . . .                                     | 89         |
| 6.2.2    | Operating point-dependent thermal parameters . . . . .           | 90         |
| 6.2.3    | Cooling scenarios . . . . .                                      | 94         |
| 6.3      | Results and discussion . . . . .                                 | 96         |
| 6.3.1    | Exemplary charging procedure . . . . .                           | 96         |
| 6.3.2    | Effect of variable through-plane thermal conductivity . . . . .  | 98         |
| 6.3.3    | Effect of aged through-plane thermal conductivity . . . . .      | 100        |
| 6.3.4    | Effect of variable specific heat capacity . . . . .              | 102        |
| 6.3.5    | Effect of variable thermal parameters on charging time . . . . . | 104        |
| 6.4      | Summary . . . . .                                                | 107        |
| <b>7</b> | <b>Conclusion</b>                                                | <b>109</b> |
|          | <b>List of abbreviations</b>                                     | <b>113</b> |
|          | <b>List of tables</b>                                            | <b>115</b> |
|          | <b>List of figures</b>                                           | <b>117</b> |
|          | <b>Bibliography</b>                                              | <b>119</b> |

|                          |            |
|--------------------------|------------|
| <b>Publications</b>      | <b>141</b> |
| <b>Curriculum Vitae</b>  | <b>143</b> |
| <b>Supervised thesis</b> | <b>145</b> |