# Contents

**Preface** . . . . . ix

**Chapter 1. Introduction to Hydrogen Technology** . . . . . 1

1.1. Hydrogen as an energy vector . . . . . 2
1.1.1. Production methods . . . . . 7
1.1.2. Storage technologies . . . . . 9
1.1.3. Distribution networks and associated risks . . . . . 10
1.1.4. Advantages and challenges to raise . . . . . 11
1.2. Types of fuel cell . . . . . 12
1.2.1. The different fuel cell technologies . . . . . 13
1.2.2. Fuel cell and their applications . . . . . 32
1.2.3. Advantages and issues to improve . . . . . 34
1.3. The proton-exchange membrane fuel cell . . . . . 35
1.3.1. The basic structure of the PEMFC . . . . . 37
1.3.2. PEMFC design and configuration . . . . . 45
1.3.3. Operation and aging problem . . . . . 47
1.3.4. The fuel cell and its technical system entourage technique . . . . . 48
1.4. Conclusion . . . . . 50
1.5. Questions . . . . . 51

**Chapter 2. Charge Transfer Phenomena** . . . . . 53

2.1. Introduction. . . . . 53
2.2. Thermodynamics and chemistry of the PEM fuel cell . . . . . 54
2.2.1. The base reaction . . . . . 54
2.2.2. Heat reaction. . . . . 54
2.2.3. Electrical work . . . . . 55

2.2.4. Empty voltage . . . 57
2.2.5. Effect of pressure . . . 58
2.2.6. Effect of temperature . . . 59
2.2.7. Theoretical efficiency . . . 63
2.3. The flow rates of reactants and products . . . 65
2.3.1. Oxygen flow rate . . . 65
2.3.2. Hydrogen flow rate . . . 66
2.3.3. Amount of water produced . . . 67
2.4. Electrochemistry of the fuel cell . . . 67
2.4.1. Electrode kinetics . . . 67
2.4.2. Activation energy . . . 68
2.4.3. Reaction rate . . . 69
2.4.4. Exchange current . . . 69
2.4.5. Current density . . . 71
2.5. Polarization phenomena . . . 72
2.5.1. Activation polarization . . . 72
2.5.2. Ohmic polarization . . . 74
2.5.3. Concentration polarization . . . 75
2.5.4. Real cell voltage . . . 77
2.5.5. Polarization curve . . . 77
2.5.6. Optimum operating range . . . 79
2.6. Modeling of charge transfer . . . 79
2.7. Overview of analytical models . . . 79
2.7.1. Simple analytical models . . . 80
2.7.2. Complex analytical models . . . 80
2.8. Empirical models . . . 80
2.9. Current transport and charge conservation . . . 81
2.10. Conclusion . . . 82

**Chapter 3. Mass Transfer Phenomena** . . . 85

3.1. Introduction . . . 85
3.2. Flow of matter . . . 85
3.3. Mass transfer by convection . . . 90
3.4. Mass transfer in porous diffusers . . . 92
3.4.1. Conservation of mass . . . 92
3.4.2. The conservation of species . . . 93
3.4.3. Some parametric laws . . . 98
3.5. Mass transfer in the catalyst layers (electrodes) . . . 101
3.5.1. Low current model (Butler–Volmer) . . . 102
3.5.2. Agglomerate model with strong current . . . 103

3.6. Mass transfer in the membrane . . . . . 105
3.6.1. Schröeder's paradox . . . . . 106
3.6.2. Microscopic scale . . . . . 107
3.6.3. Mesoscopic scale . . . . . 110
3.6.4. Macroscopic scale . . . . . 112
3.6.5. Parametric laws . . . . . 121
3.7. Conclusion . . . . . 124

**Chapter 4. Heat Transfer Phenomena** . . . . . 125

4.1. Introduction . . . . . 125
4.2. Energy balances for a PEMFC . . . . . 127
4.2.1. Energy balance for a stack . . . . . 127
4.2.2. Energy balance for compounds and gases . . . . . 130
4.2.3. Energy balance for the gas phase . . . . . 130
4.2.4. Energy balance for the solid structure . . . . . 131
4.3. The heat flow in the different layers of the PEMFC . . . . . 131
4.3.1. Heat transfer by conduction . . . . . 132
4.3.2. Heat dissipation by natural convection and radiation . . . . . 133
4.4. Thermal management in a PEMFC . . . . . 134
4.4.1. Cooling systems . . . . . 134
4.4.2. Convection cooling of the airflow at the cathode . . . . . 134
4.4.3. The effect of temperature on the performance of the PEMFC . . . . . 138
4.5. Heat sources in the PEMFC . . . . . 138
4.5.1. In the polymer membrane . . . . . 140
4.5.2. At the electrodes . . . . . 141
4.5.3. In the GDLs . . . . . 143
4.5.4. Water evaporation and condensation . . . . . 145
4.6. Temperature distribution between two cathodes: case study . . . . . 147
4.7. Conclusion . . . . . 152

**List of Symbols** . . . . . 155

**Bibliography** . . . . . 159

**Index** . . . . . 175