

# Contents

<b>Acknowledgements</b>	<b>i</b>
<b>Abstract (English/Français/Deutsch)</b>	<b>v</b>
<b>List of Figures</b>	<b>xv</b>
<b>List of Tables</b>	<b>xxiii</b>
<b>List of Acronyms</b>	<b>xxv</b>
<b>List of Symbols</b>	<b>xxix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation . . . . .	1
1.2 History of energy modeling, turbomachinery, and SOFC research at EPFL . . . . .	2
1.3 Objectives and organization . . . . .	3
1.4 Aspects of novelty . . . . .	5
<b>2 State of the Art</b>	<b>7</b>
2.1 Solid oxide fuel cell system . . . . .	7
2.1.1 Basic principles . . . . .	7
2.1.2 Cell composition . . . . .	8
2.1.3 Fuel reforming . . . . .	8
2.1.4 Stack and its efficiency . . . . .	11
2.1.5 Stationary systems . . . . .	13
2.1.6 System efficiency . . . . .	16
2.1.7 Off-gas recirculation . . . . .	17
2.1.8 Carbon deposition . . . . .	20
2.1.9 Research systems . . . . .	21
2.2 Pressure rise units for off-gas recirculation . . . . .	24
2.2.1 Specifications of the pressure rise unit . . . . .	26
2.2.2 Commercial and research recirculation fans . . . . .	27
2.2.3 Comparison of different pressure rise unit technologies . . . . .	28
2.3 Fan . . . . .	31
2.3.1 Nomenclature . . . . .	31

2.3.2	Velocity triangles and mean-line analysis . . . . .	33
2.3.3	Efficiency and power . . . . .	36
2.3.4	Similarity concepts and scaling laws . . . . .	39
2.3.5	Design procedure and concepts . . . . .	44
2.4	Turbine . . . . .	49
2.5	Intellectual property . . . . .	51
<b>3</b>	<b>SOFC System Design</b>	<b>53</b>
3.1	SOFC system with thermally-driven anode off-gas recirculation fan . . . . .	53
3.2	Methodology . . . . .	54
3.3	Modeling . . . . .	57
3.3.1	Energy flow model . . . . .	57
3.3.2	Small-scale turbomachinery model . . . . .	60
3.3.3	Heat and power integration . . . . .	64
3.3.4	Performance objectives and multi-objective optimization . . . . .	64
3.4	Results and analysis . . . . .	65
3.5	Heat exchanger network design (baseline SOFC system) . . . . .	72
3.6	Sensitivity of steam leakage (baseline SOFC system) . . . . .	73
3.7	Chapter conclusion . . . . .	74
<b>4</b>	<b>Fan-Turbine Unit Design</b>	<b>77</b>
4.1	Small-scale turbomachinery . . . . .	77
4.2	Design procedure of the anode off-gas recirculation unit . . . . .	77
4.3	Fan-turbine unit concept and bearing design . . . . .	78
4.3.1	Concept of the fan-turbine unit . . . . .	78
4.3.2	Gas film bearing and shaft design . . . . .	80
4.4	Radial fan . . . . .	82
4.4.1	Fan specifications . . . . .	82
4.4.2	Fan design summary . . . . .	82
4.4.3	One-dimensional simulation . . . . .	85
4.4.4	Three-dimensional single passage simulation . . . . .	90
4.4.5	Three-dimensional full passage simulation . . . . .	107
4.5	Radial-inflow turbine . . . . .	109
4.5.1	Turbine specifications . . . . .	109
4.5.2	Turbine design summary . . . . .	111
4.5.3	Zero and one-dimensional simulation . . . . .	119
4.5.4	Three-dimensional single passage simulation . . . . .	122
4.5.5	Three-dimensional full passage simulation . . . . .	129
4.6	Thrust force model . . . . .	133
4.7	Chapter conclusion . . . . .	137

<b>5</b>	<b>Fan-Turbine Unit Experiments</b>	<b>141</b>
5.1	Fan-turbine unit propelled by nozzles with pressurized ambient air . . . . .	141
5.2	Turbine propelled by pressurized ambient air . . . . .	145
5.3	Fan and turbine operated with ambient air . . . . .	149
5.4	Calculation of turbomachinery parameters . . . . .	152
5.4.1	Evaluation of the leakage from the turbine to the fan . . . . .	155
5.4.2	Influence of the leakage and heat on the turbomachine power and efficiency	156
5.5	Fan and turbine operated with hot air at 200 °C . . . . .	158
5.6	Fan operated with hot air at 200 °C and turbine operated with water vapor at 220 °C . . . . .	166
5.7	Chapter conclusion . . . . .	171
<b>6</b>	<b>Integration of the Fan-Turbine Unit with the SOFC System</b>	<b>175</b>
6.1	Measurement setup . . . . .	175
6.2	Test at ambient conditions . . . . .	177
6.3	Test with operational SOFC . . . . .	179
6.4	Chapter conclusion . . . . .	184
<b>7</b>	<b>Summary and Conclusions</b>	<b>185</b>
7.1	Summary . . . . .	185
7.2	Future work . . . . .	186
<b>A</b>	<b>Commercial, Precommercial, and Postcommercial SOFC Systems</b>	<b>189</b>
<b>B</b>	<b>Mesh Sensitivity Analysis for the Fan Impeller</b>	<b>193</b>
<b>C</b>	<b>Measurement Uncertainty and Calibration of Equipment</b>	<b>195</b>
<b>D</b>	<b>Balancing of the Fan-Turbine Unit</b>	<b>203</b>
<b>E</b>	<b>Turbine Stator Blockage</b>	<b>207</b>
	<b>Bibliography</b>	<b>218</b>
	<b>List of Academic Activities</b>	<b>219</b>
	<b>List of Publications</b>	<b>221</b>
	<b>Curriculum Vitae</b>	<b>223</b>