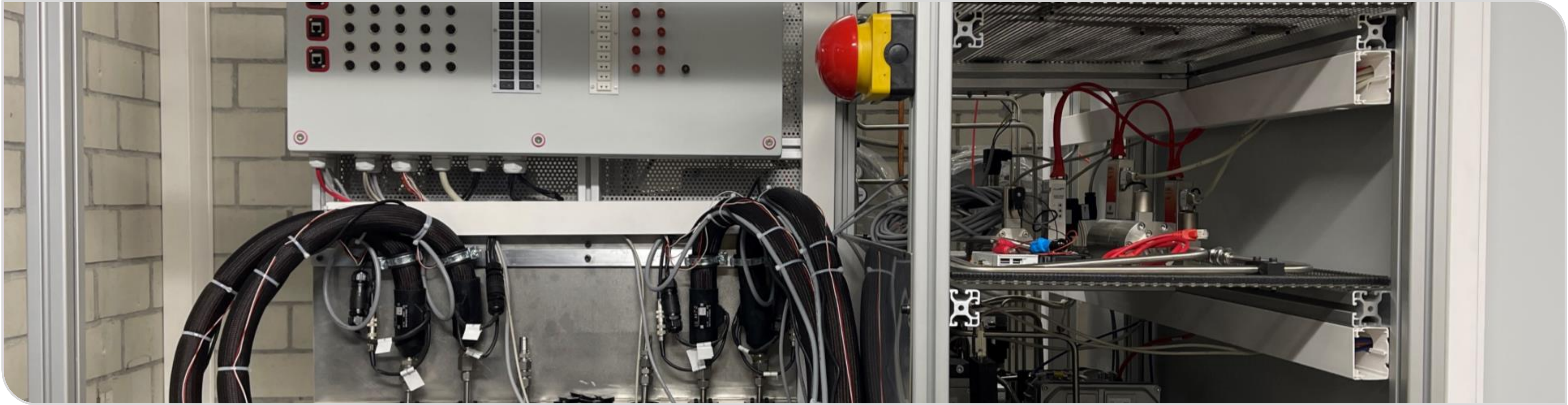
PEMFC System Evaluation: A Comprehensive Test Bench Approach across Cell, Stack and System Levels

Johannes Knaier, M. Sc.

IPEK – Institute of Product Engineering at Karlsruhe Institute of Technology (KIT)



Subject Introduction
System, Stack and Cell Level of PEMFCs in mobile Applications

System Level

Legend: **Levels**, ***subsystems*** & <u>sub-subsystems</u>

Hydrogen supply
- <u>Hydrogen tank</u>
  - Choke valve
- <u>Anode recirculation</u>
  - Active / passive recirculation pump
  - Purge valve
  - Condensate separator

Air supply
- <u>Air compression</u>
  - Turbo compressor
- <u>Air humidification</u>
  - Membrane humidifier
- <u>Air purification</u>
  - Air filter

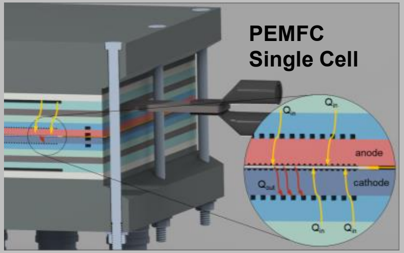
Thermal management
- <u>Coolant supply</u>
  - Coolant pump
  - Heat exchanger
- <u>Heat supply</u>
  - Heating elements

Power electronics
- <u>Voltage converter</u>
- <u>Battery system</u>
- <u>Control and regulation technology</u>

PEMFC test bench

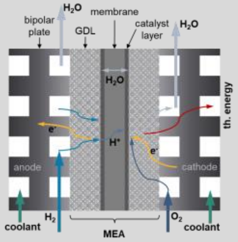
Stack Level

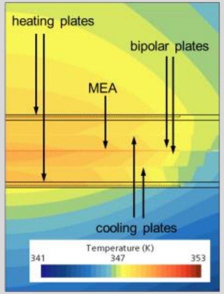
Fuel cell stack
- <u>Sealing concept</u>
- <u>Compression concept</u>
- <u>Insulation</u>
- <u>Current collector</u>
- <u>Media modules</u>



Cell Level

Fuel cell
- <u>Bipolar plates</u>
- <u>Polymer membrane</u>
- <u>Subgasket</u>
- <u>Gas diffusion layer</u>





WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

Subject Introduction
Driving cycles, load profiles and system interactions in FCEV

Karlsruhe Institute of Technology

Driving condition **External framwork**	Driving cycle **Start & Stop**	Driving cycle **Acceleration**	Driving cycle **Idling**	Driving cycle **Speed cycling**	Driving cycle **Constant speed**
Environment/ weather & road situations	Sytem start up / start of the driving cycle	Overtaking maneuver/ ascent	Running system without power output/ descent	Dynamic driving situation/ usually city miles	Long distance/ usually highway miles
Driving distance/ long vs. short	System shut down / end of the driving cycle	Increasing power demand	Decreasing power demand	Dynamic power demand	Constant power demand

PEMFC load profile **Potential cycling**	PEMFC load profile **Open circuit voltage**	PEMFC load profile **Extra-high current density**	PEMFC load profile **Extra-low current density**	PEMFC load profile **Current density cycling**	PEMFC load profile **Constant current density**
Variable gas flow rates	No fuel flow rates	High gas flow rates	Low gas flow rates [5]	Variable gas flow rates	Constant gas flow rates
Variable H_2O production	Low H_2O production [3]	High H_2O production [1]	High H_2O (l) production [1]	Variable H_2O production [3]	Constant H_2O production
Variable thermal output	No thermal output	High thermal output [1]	Low thermal output	Variable thermal output [3]	Constant thermal output
Inconsistent gas supply	Severe gas crossover [3]	Gas starvation	Severe gas crossover	Gas starvation [3]	Consistent gas supply
	High cathode potential [3]		High overall cell voltage [1]		**Optimal load profile** [1]

System level

Stack level

Cell level

WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

IPEK Institute of Product Engineering at Karlsruhe Institute of Technology

Subject Introduction
Driving cycles, load profiles and system interactions in FCEV

PEMFC load profile **Potential cycling**	PEMFC load profile **Open circuit voltage**	PEMFC load profile **Extra-high current density**	PEMFC load profile **Extra-low current density**	PEMFC load profile **Current density cycling**	PEMFC load profile **Constant current density**
Variable gas flow rates	No fuel flow rates	High gas flow rates	Low gas flow rates [5]	Variable gas flow rates	Constant gas flow rates
Variable H_2O production	Low H_2O production [3]	High H_2O production [1]	High H_2O (l) production [1]	Variable H_2O production [3]	Constant H_2O production
Variable thermal output	No thermal output	High thermal output [1]	Low thermal output	Variable thermal output [3]	Constant thermal output
Inconsistent gas supply	Severe gas crossover [3]	Gas starvation	Severe gas crossover	Gas starvation [3]	Consistent gas supply
	High cathode potential [3]		High overall cell voltage [1]		**Optimal load profile** [1]

System level

Stack level

Cell level

PEMFC **Bipolar plates**	PEMFC **Polymer membrane**	PEMFC **Subgasket**	PEMFC **Gas diffusion layer**
Flow field	Catalyst	MEA stiffness	Porosity
Coating	Thickness	Sealing and insulation of MEA to BPP	Hydrophile vs. hydrophobe

PEMFC Stack **Sealing concept**	PEMFC Stack **Compression concept**	PEMFC Stack **Media modules**	PEMFC Stack **Current collector**
Positioning and dislocation	Stack breathing	Fluid distribution	Internal conductivity
Dependent on temperature	Force distribution	Connection interface stack / system level	Bridging electron flow with ext system

WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

Subject Introduction

Driving cycles, load profiles and system interactions in FCEV

System level

Stack level

Cell level

PEMFC **Bipolar plates**	PEMFC **Polymer membrane**	PEMFC **Subgasket**	PEMFC **Gas diffusion layer**
Flow field	Catalyst	MEA stiffness	Porosity
Coating	Thickness	Sealing and insulation of MEA to BPP	Hydrophile vs. hydrophobe
PEMFC Stack **Sealing concept**	PEMFC Stack **Compression concept**	PEMFC Stack **Media modules**	PEMFC Stack **Current collector**
Positioning and dislocation	Stack breathing	Fluid distribution	Internal conductivity
Dependent on temperature	Force distribution	Connection interface stack / system level	Bridging electron flow with ext system
PEMFC System **Hydrogen supply management**	PEMFC System **Air supply management**	PEMFC System **Thermal & water management**	PEMFC System **Electrical power management**
Hydrogen tank and choke valve	Air compression	Coolant supply and heat exchanger	Voltage converter and battery system
Anode recirculation and purge valve	Air purification	Air humidifier	Control and regulation unit

WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

Subject Introduction
Driving cycles, load profiles and system interactions in FCEV

Positioning and dislocation Dependent on temperature	Stack breathing Force distribution	Fluid distribution Connection interface stack / system level	Internal conductivity Bridging electron flow with ext system
PEMFC System **Hydrogen supply management**	PEMFC System **Air supply management**	PEMFC System **Thermal & water management**	PEMFC System **Electrical power management**
Hydrogen tank and choke valve Anode recirculation and purge valve	Air compression Air purification	Coolant supply and heat exchanger Air humidifier	Voltage converter and battery system Control and regulation unit

Key factor	Key factor	Key factor	Key factor	Key factor	Key factor
Mechanical vibration	**Low water production / dehydration**	**Cathode flooding**	**Anode flooding**	**Fuel starvation**	**Air starvation**
Certain frequencies and amplitudes have an effect on water transport and can cause flooding [8] (decrease in current density) Causes shear stresses between BP, GDL and MEA and leads to MEA thinning [9] (increase in hydrogen crossover rate)	Increased membrane resistance and decreased proton conductivity [6, 7] (reducing overall efficieny) Membrane thinning [4] (increment of gas crossover) Formation of pin holes in membrane [4] (enhance membrane degradation)	Found at high current densities, where more water is created and a higher electro-osmosis flux occurs [1] (local gas starvation)	Occurs at low current densities, where fuel flow rates are insufficient to prevent the accumulation of liquid water [5] (local gas starvation)	Insufficient hydrogen supply leads to a voltage drop due to imbalanced electro-chemical reactions [10] Causes the anode to undergo undesirable oxidation reactions [3, 11] (results in carbon corrosion)	Lowers output voltage due to abrupt decrease of cathode potential [3] (overall air starvation can lead to ceell reversal) Due to high potential difference, hydrogen can diffuse to cathode side and react directly with oxygen [3] (causing the formation of hot spots)
		Key factor **Pressure**	Key factor **Temperature**	Key factor	

WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

Subject Introduction

Driving cycles, load profiles and system interactions in FCEV

Key factor
Mechanical vibration

Certain frequencies and amplitudes have an effect on water transport and can cause flooding [8] (decrease in current density)

Causes shear stresses between BP, GDL and MEA and leads to MEA thinning [9] (increase in hydrogen crossover rate)

Key factor
Pollutants & impurities

Results from improper hydrogen fuel or air contamination

CO, CO_2, NH_3, H_2S, SO_2 can lead to degradation [2]

Key factor
Low water production / dehydration

Increased membrane resistance and decreased proton conductivity [6, 7] (reducing overall efficieny)

Membrane thinning [4] (increment of gas crossover)

Formation of pinholes in membrane [4] (enhance membrane degradation)

Key factor
Freezing & thawing

Ice formation leads to expansion and mechanical stress

Key factor
Cathode flooding

Found at high current densities, where more water is created and a higher electro-osmosis flux occurs [1] (local gas starvation)

Key factor
Pressure

Pressure plays a pivotal role, influencing electrochemical reaction rates, cell voltage, gas diffusion, water management, membrane hydration and mechanical stress.

Key factor
Anode flooding

Occurs at low current densities, where fuel flow rates are insufficient to prevent the accumulation of liquid water [5] (local gas starvation)

Key factor
Temperature

Temperature exerts a significant influence on the water balance and the diffusion rates of H_2 and O_2.

Key factor
Fuel starvation

Insufficient hydrogen supply leads to a voltage drop due to imbalanced electo-chemical reactions [10]

Causes the anode to undergo undesirable oxidation reactions [3, 11] (results in carbon corrosion)

Key factor
Humidity cycling

Fluctuations in humidity lead to cyclic expansion and contraction of the membrane (mechanical stress and potential cracks and pinholes)

Key factor
Air starvation

Lowers output voltage due to abrupt decrease of cathode potential [3] (overall air starvation can lead to ceell reversal)

Due to high potential difference, hydrogen can diffuse to cathode side and react directly with oxygen [3] (causing the formation of hot spots)

WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

Subject Introduction
Research areas of PEMFCs for mobile applications

Karlsruhe Institute of Technology

→ **Research objectives – state of research**

- Performance improvement
- Extension of service life
- Reduction of costs

- Material research [1-24]
- System integration and optimization [26-43]
- Operating strategies and management [51-62]

→ **Research gap:** Research tends to focus on one of these areas

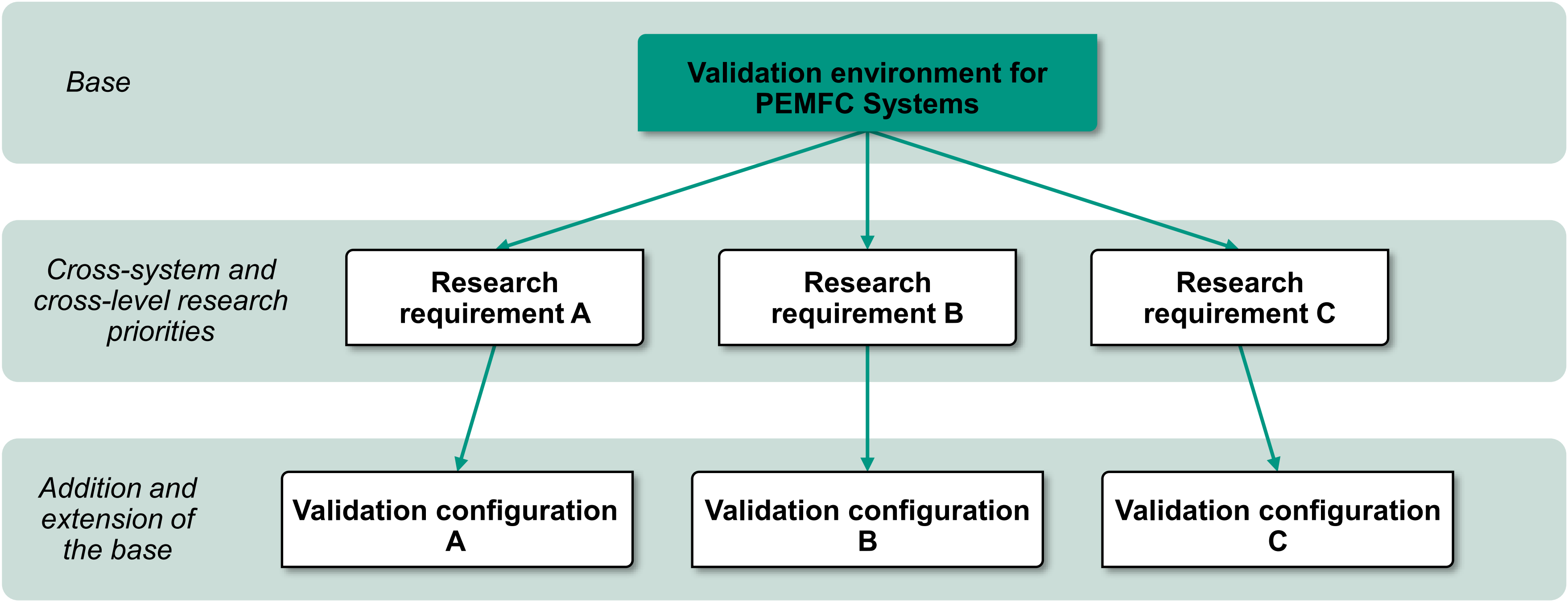
- Holistic view often falls by the wayside
  - Interactions between balance of plant components are often not considered
  - No consistent external framework

→ **Research requirements:**

A validation environment is required that emulates all balance-of-plant components relevant to the operation of the PEMFC, allowing the analysis of a complete PEMFC system with all its subsystems.

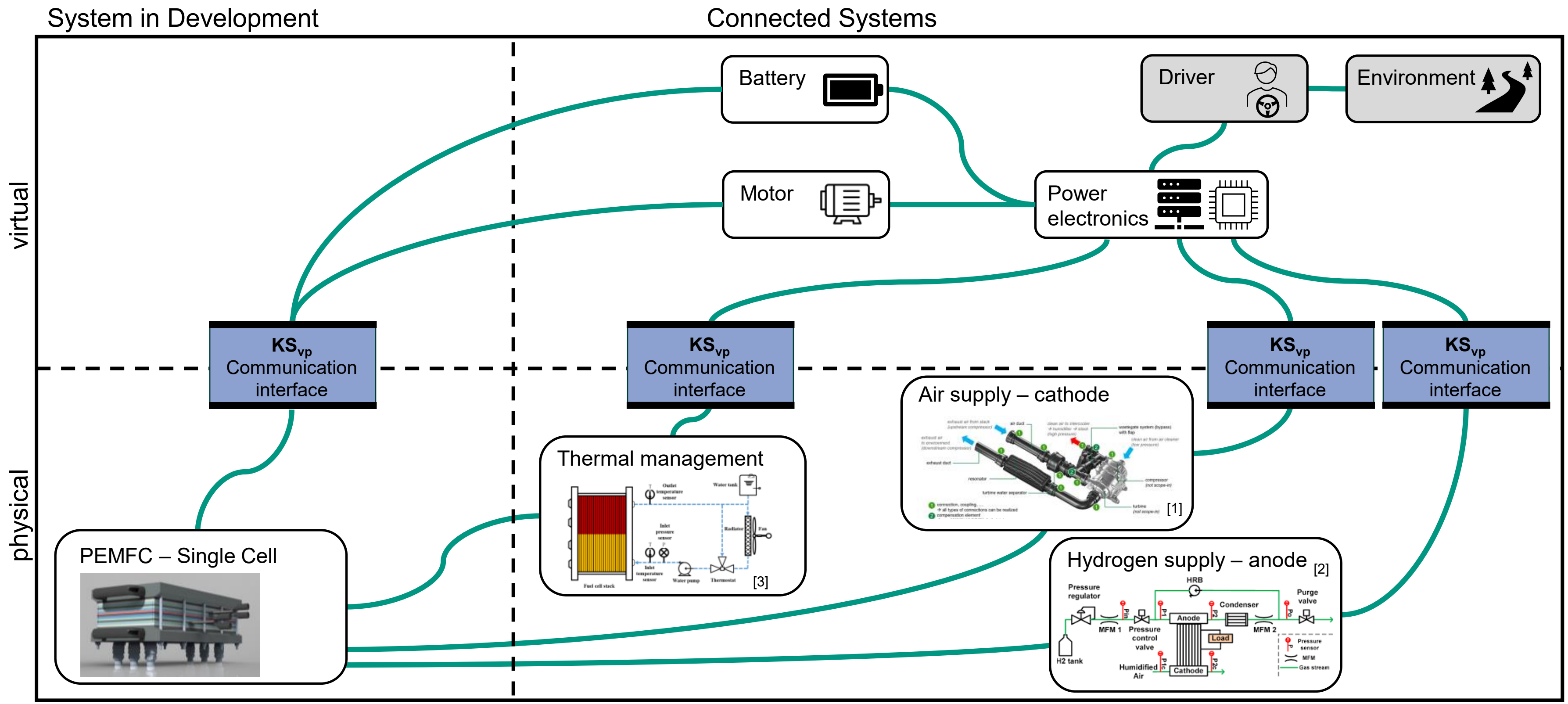
- Long-term value
  - Analysis of interactions between subsystems and their impact on the system-in-development
  - Research focus across subsystems and levels

PEMFC System Evaluation
Validation environment



PEMFC System Evaluation

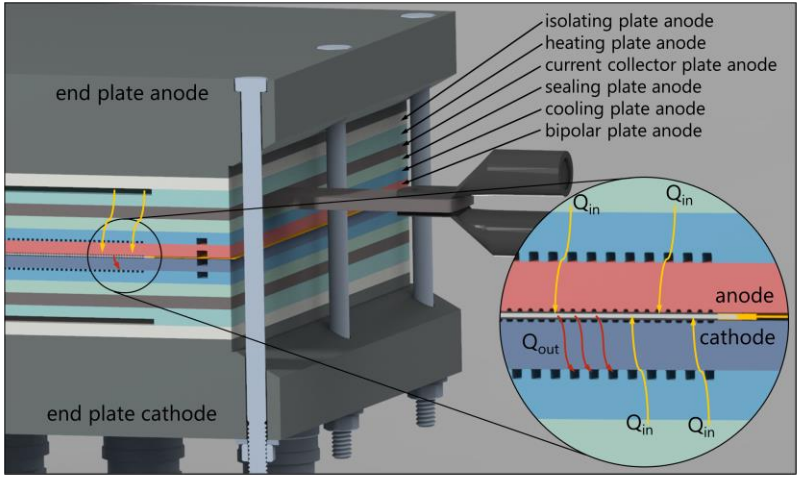
Model of the architecture of the base validation configuration – IPEK XiL

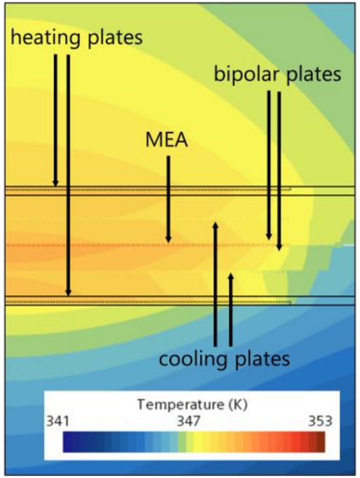


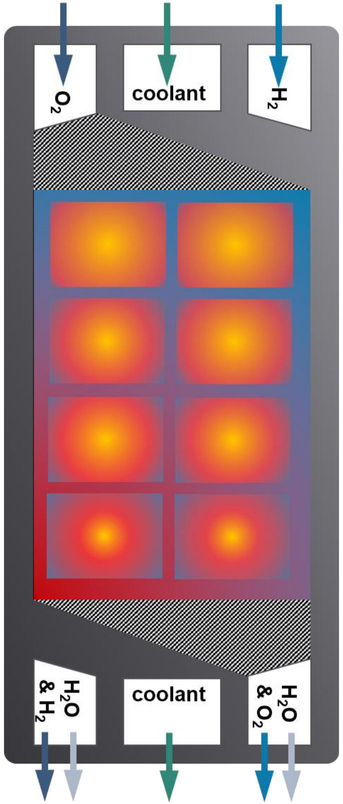
WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

PEMFC System Evaluation
Validation configuration

- **Validation configuration A**
  - *Emulating thermal management of a complete fuel cell stack → virtual System in Development*
    - PEMFC Stack through **heating elements** as “Koppelsystems”
      - Interactions of thermal distribution between neighboring cells and their impact on thermal management as *physical connected system*



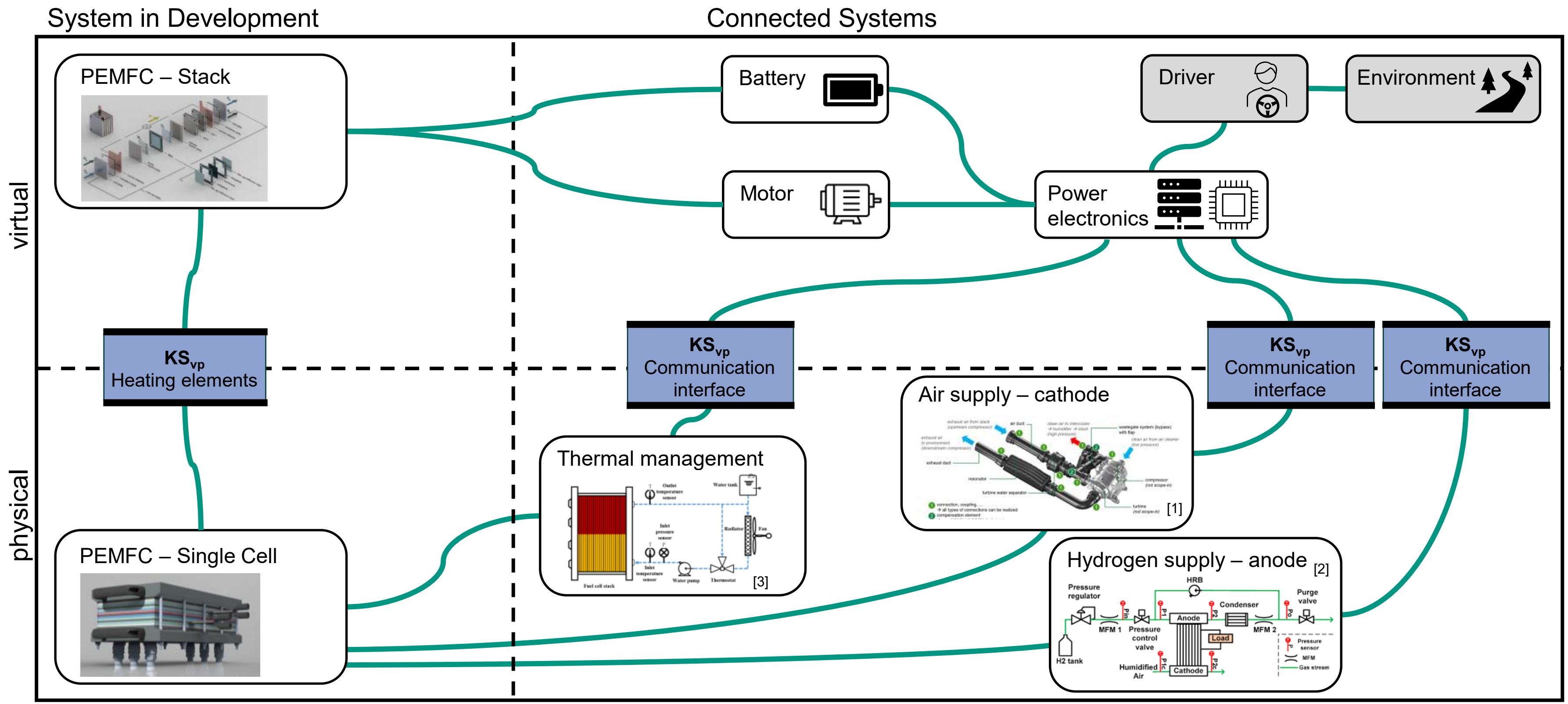




WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

PEMFC System Evaluation

Model of the architecture of the validation configuration A – IPEK XiL



WHEC – 24th World Hydrogen Energy Conference 23 - 27 June 2024, Johannes Knaier M.Sc.
johannes.knaier@kit.edu, IPEK – Institute of Product Engineering

Karlsruhe Institute of Technology

Thank you for your attention!

WHEC-2024
24TH WORLD HYDROGEN ENERGY CONFERENCE

IPEK
Institut für Produktentwicklung

LinkedIn

INNOVATIONSCAMPUS
MOBILITÄT DER ZUKUNFT

The authors would like to thank the Ministry of Science, Research and Arts of the Federal State of Baden-Württemberg for the financial support of the projects within the InnovationCampus Future Mobility (ICM).

Sources
Driving cycles, load profiles and system interactions in FCEV

[1] Zhang, Xinfeng; Yang, Daijun; Luo, Minghui; Dong, Zuomin (2017): Load profile based empirical model for the lifetime prediction of an automotive PEM fuel cell. In: International Journal of Hydrogen Energy 42 (16), S. 11868–1878. DOI: 10.1016/j.ijhydene.2017.02.146.

[2] Zhao, Yinqi; Mao, Yejun; Zhang, Weixian; Tang, Yanli; Wang, Peizhen (2020): Reviews on the effects of contaminations and research methodologies for PEMFC. In: International Journal of Hydrogen Energy 45 (43), S. 23174–3200. DOI: 10.1016/j.ijhydene.2020.06.145.

[3] Ren, Peng; Pei, Pucheng; Li, Yuehua; Wu, Ziyao; Chen, Dongfang; Huang, Shangwei (2020): Degradation mechanisms of proton exchange membrane fuel cell under typical automotive operating conditions. In: Progress in Energy and Combustion Science 80, S. 100859. DOI: 10.1016/j.pecs.2020.100859.

[4] Sorrentino, Antonio; Sundmacher, Kai; Vidakovic-Koch, Tanja (2020): Polymer Electrolyte Fuel Cell Degradation Mechanisms and Their Diagnosis by Frequency Response Analysis Methods: A Review. In: Energies 13 (21), S. 5825. DOI: 10.3390/en13215825.

[5] O'Rourke, Judith; Ramani, Manikandan; Arcak, Murat (2009): In situ detection of anode flooding of a PEM fuel cell. In: International Journal of Hydrogen Energy 34 (16), S. 6765–770. DOI: 10.1016/j.ijhydene.2009.06.029.

[6] Raman, Srinivasan; Iyeswaria, K. B.; Narasimhan, Sridharakumar; Rengaswamy, Raghunathan (2017): Effects of water induced pore blockage and mitigation strategies in low temperature PEM fuel cells –A simulation study. In: International Journal of Hydrogen Energy 42 (37), S. 23799–3813. DOI: 10.1016/j.ijhydene.2017.03.174.

[7] Zaveri, Jaydev Chetan; Dhanushkodi, Shankar Raman; Kumar, C. Ramesh; Taler, Jan; Majdak, Marek; Węlowski, Bohdan (2023): Predicting the Performance of PEM Fuel Cells by Determining Dehydration or Flooding in the Cell Using Machine Learning Models. In: Energies 16 (19), S. 6968. DOI: 10.3390/en16196968.

[8] Wang, Xueke; Wang, Shubo; Chen, Sitong; Zhu, Tong; Xie, Xiaofeng; Mao, Zhiming (2016): Dynamic response of proton exchange membrane fuel cell under mechanical vibration. In: International Journal of Hydrogen Energy 41 (36), S. 16287–6295. DOI: 10.1016/j.ijhydene.2016.06.082.

[9] Diloyan, Georgiy; Sobel, Marcus; Das, Kiranmoy; Hutapea, Parsaoran (2012): Effect of mechanical vibration on platinum particle agglomeration and growth in Polymer Electrolyte Membrane Fuel Cell catalyst layers. In: Journal of Power Sources 214, S. 59–7. DOI: 10.1016/j.jpowsour.2012.04.027.

[10] Du, Fengmin; Hirschfeld, Julian Arndt; Huang, Xinyi; Jozwiak, Krzysztof; Dao, Tuan Anh; Bauer, Andreas et al. (2021): Simulative Investigation on Local Hydrogen Starvation in PEMFCs: Influence of Water Transport and Humidity Conditions. In: Journal of The Electrochemical Society 168 (7). DOI: 10.1149/1945-7111/ac148e.

[11] Meng, Kai; Chen, Ben; Zhou, Haoran; Shen, Jun; Tu, Zhengkai (2022): Experimental investigation on voltage response characteristics of hydrogen-oxygen proton exchange membrane fuel cells under gas starvation. In: Energy Conversion and Management 268, S. 115973. DOI: 10.1016/j.enconman.2022.115973.

Sources
Research areas of PEMFC for mobile applications

Karlsruhe Institute of Technology

[1] Ming Chen, Chen Zhao, Fengman Sun, Jiantao Fan, Hui Li, Haijiang Wang, Research progress of catalyst layer and interlayer interface structures in membrane electrode assembly (MEA) for proton exchange membrane fuel cell (PEMFC) system, eTransportation, Volume 5, **2020**, 100075, ISSN 2590-1168, https://doi.org/10.1016/j.etran.2020.100075. (https://www.sciencedirect.com/science/article/pii/S2590116820300321)
[2] Martin Prokop, Monika Drakselova, Karel Bouzek, Review of the experimental study and prediction of Pt-based catalyst degradation during PEM fuel cell operation, Current Opinion in Electrochemistry, Volume 20, **2020**, Pages 20-27, ISSN 2451-9103, https://doi.org/10.1016/j.coelec.2020.01.016. (https://www.sciencedirect.com/science/article/pii/S2451910320300235)
[3] Bee Huah Lim, Edy Herianto Majlan, Ahmad Tajuddin, Teuku Husaini, Wan Ramli Wan Daud, Nabilah Afiqah Mohd Radzuan, Md. Ahsanul Haque, Comparison of catalyst-coated membranes and catalyst-coated substrate for PEMFC membrane electrode assembly: A review, Chinese Journal of Chemical Engineering, Volume 33, **2021**, Pages 1-16, ISSN 1004-9541, https://doi.org/10.1016/j.cjche.2020.07.044. (https://www.sciencedirect.com/science/article/pii/S1004954120304158)
[4] Stefanos Tzelepis, Kosmas A. Kavadias, George E. Marnellos, George Xydis, A review study on proton exchange membrane fuel cell electrochemical performance focusing on anode and cathode catalyst layer modelling at macroscopic level, Renewable and Sustainable Energy Reviews, Volume 151, **2021**, 111543, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.111543. (https://www.sciencedirect.com/science/article/pii/S1364032121008212)
[5] Hong Wang, Rui Lin, Xin Cai, Shengchu Liu, Di Zhong, Zhixian Hao, Transition metal dissolution control in Pt-alloy catalyst layers for low Pt-loaded PEMFCs for improving mass transfer, International Journal of Heat and Mass Transfer, Volume 178, **2021**, 121615, ISSN 0017-9310, https://doi.org/10.1016/j.ijheatmasstransfer.2021.121615. (https://www.sciencedirect.com/science/article/pii/S0017931021007183)
[6] Lixin Fan, Junjie Zhao, Xiaobing Luo, Zhengkai Tu, Comparison of the performance and degradation mechanism of PEMFC with Pt/C and Pt black catalyst, International Journal of Hydrogen Energy, Volume 47, Issue 8, **2022**, Pages 5418-5428, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.11.135. (https://www.sciencedirect.com/science/article/pii/S0360319921045225)

[7] Paul C. Okonkwo, Ikram Ben Belgacem, Wilfred Emori, Paul C. Uzoma, Nafion degradation mechanisms in proton exchange membrane fuel cell (PEMFC) system: A review, International Journal of Hydrogen Energy, Volume 46, Issue 55, **2021**, Pages 27956-27973, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.06.032. (https://www.sciencedirect.com/science/article/pii/S0360319921021832)
[8] Yijing Xing, Haibin Li, George Avgouropoulos, Research Progress of Proton Exchange Membrane Failure and Mitigation Strategies, Materials **2021**, 14(10), 2591; https://doi.org/10.3390/ma14102591. (https://www.mdpi.com/1996-1944/14/10/2591)
[9] Y. Prykhodko, K. Fatyeyeva, L. Hespel, S. Marais, Progress in hybrid composite Nafion®-based membranes for proton exchange fuel cell application, Chemical Engineering Journal, Volume 409, **2021**, 127329, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2020.127329. (https://www.sciencedirect.com/science/article/pii/S1385894720334537)
[10] Tushar Kanti Maiti, Jitendra Singh, Jagannath Majhi, Arihant Ahuja, Subrata Maiti, Prakhar Dixit, Sakchi Bhushan, Anasuya Bandyopadhyay, Sujay Chattopadhyay, Advances in polybenzimidazole based membranes for fuel cell applications that overcome Nafion membranes constraints, Polymer, Volume 255, **2022**, 125151, ISSN 0032-3861, https://doi.org/10.1016/j.polymer.2022.125151. (https://www.sciencedirect.com/science/article/pii/S0032386122006395)
[11] Li-Yu Zhu, Yu-Cheng Li, Jing Liu, Jing He, Lu-Ying Wang, Jian-Du Lei, Recent developments in high-performance Nafion membranes for hydrogen fuel cells applications, Petroleum Science, Volume 19, Issue 3, **2022**, Pages 1371-1381, ISSN 1995-8226, https://doi.org/10.1016/j.petsci.2021.11.004. (https://www.sciencedirect.com/science/article/pii/S1995822621001382)
[12] Xiaojing Cheng, Jiabin You, Shuiyun Shen, Guanghua Wei, Xiaohui Yan, Chao Wang, Junliang Zhang, An ingenious design of nanoporous nafion film for enhancing the local oxygen transport in cathode catalyst layers of PEMFCs, Chemical Engineering Journal, Volume 439, **2022**, 135387, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2022.135387. (https://www.sciencedirect.com/science/article/pii/S1385894722008907)

[13] Yinqi Zhao, Yejun Mao, Weixian Zhang, Yanli Tang, Peizhen Wang, Reviews on the effects of contaminations and research methodologies for PEMFC, International Journal of Hydrogen Energy, Volume 45, Issue 43, **2020**, Pages 23174-23200, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2020.06.145. (https://www.sciencedirect.com/science/article/pii/S0360319920323004)
[14] Veeresh Patil, P.V. Reshmi, S. Prajna, Yashaswi, Yashaswini, D. Haleshappa, A. Jayarama, Richard Pinto, Degradation mechanisms in PEM fuel cells: A brief review, Materials Today: Proceedings, **2023**, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2023.03.603. (https://www.sciencedirect.com/science/article/pii/S221478532301670X)
[15] Caizhi Zhang, Yuqi Zhang, Lei Wang, Xiaozhi Deng, Yang Liu, Jiujun Zhang, A health management review of proton exchange membrane fuel cell for electric vehicles: Failure mechanisms, diagnosis techniques and mitigation measures, Renewable and Sustainable Energy Reviews, Volume 182, **2023**, 113369, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2023.113369. (https://www.sciencedirect.com/science/article/pii/S1364032123002265)
[16] Xin Wei, Ru-Zhi Wang, Wei Zhao, Ge Chen, Mao-Rong Chai, Lei Zhang, Jiujun Zhang, Recent research progress in PEM fuel cell electrocatalyst degradation and mitigation strategies, EnergyChem, Volume 3, Issue 5, **2021**, 100061, ISSN 2589-7780, https://doi.org/10.1016/j.enchem.2021.100061. (https://www.sciencedirect.com/science/article/pii/S2589778021000117)
[17] Velia Fabiola Valdés-López, Tom Mason, Paul R. Shearing, Dan J.L. Brett, Carbon monoxide poisoning and mitigation strategies for polymer electrolyte membrane fuel cells – A review, Progress in Energy and Combustion Science, Volume 79, **2020**, 100842, ISSN 0360-1285, https://doi.org/10.1016/j.pecs.2020.100842. (https://www.sciencedirect.com/science/article/pii/S036012851930156X)
[18] Tatyana Reshetenko, Vincent Laue, Ulrike Krewer, Kateryna Artyushkova, Study of degradation and spatial performance of low Pt-loaded proton exchange membrane fuel cells under exposure to sulfur dioxide in an oxidant stream, Journal of Power Sources, Volume 458, **2020**, 228032, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2020.228032. (https://www.sciencedirect.com/science/article/pii/S0378775320303359)

[19] Yuxi Song, Caizhi Zhang, Chun-Yu Ling, Ming Han, Rui-Yuan Yong, Deen Sun, Jinrui Chen, Review on current research of materials, fabrication and application for bipolar plate in proton exchange membrane fuel cell, International Journal of Hydrogen Energy, Volume 45, Issue 54, **2020**, Pages 29832-29847, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2019.07.231. (https://www.sciencedirect.com/science/article/pii/S0360319919328745)
[20] Jiefu Shi, Pengchao Zhang, Yuetong Han, Hongyu Wang, Xinyu Wang, Yingshui Yu, Juncai Sun, Investigation on electrochemical behavior and surface conductivity of titanium carbide modified Ti bipolar plate of PEMFC, International Journal of Hydrogen Energy, Volume 45, Issue 16, **2020**, Pages 10050-10058, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2020.01.203. (https://www.sciencedirect.com/science/article/pii/S0360319920303815)
[21] Xin Gao, Jiayi Chen, Runjing Xu, Zheng Zhen, Xiantai Zeng, Xiaodong Chen, Lifeng Cui, Research progress and prospect of the materials of bipolar plates for proton exchange membrane fuel cells (PEMFCs), International Journal of Hydrogen Energy, Volume 50, Part C, **2024**, Pages 711-743, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2023.09.005. (https://www.sciencedirect.com/science/article/pii/S0360319923045688)
[22] Yu Leng, Daijun Yang, Pingwen Ming, Cunman Zhang, A comparative study of corrosion resistance evaluation of bipolar plate materials for proton exchange membrane fuel cell, eTransportation, Volume 10, **2021**, 100139, ISSN 590-1168, https://doi.org/10.1016/j.etran.2021.100139. (https://www.sciencedirect.com/science/article/pii/S2590116821000370)
[23] Kwang Il Jeong, Jaehyung Oh, Seung A Song, Dongyoung Lee, Dai Gil Lee, Seong Su Kim, A review of composite bipolar plates in proton exchange membrane fuel cells: Electrical properties and gas permeability, Composite Structures, Volume 262, **2021**, 113617, ISSN 0263-8223, https://doi.org/10.1016/j.compstruct.2021.113617. (https://www.sciencedirect.com/science/article/pii/S0263822321000787)
[24] Abhinav Srivastava, Kenneth A. Ross, Christopher B. Smith, Coating developments towards enabling aluminum as a bipolar plate material for PEM fuel cells, Journal of Power Sources, Volume 582, **2023**, 233513, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2023.233513. (https://www.sciencedirect.com/science/article/pii/S0378775323008893)

Sources
Research areas of PEMFC for mobile applications

[26] S. N. Giménez, J. M. H. Durá, F. X. B. Ferragud and R. S. Fernández, "Design and Experimental Validation of the Temperature Control of a PEMFC Stack by Applying Multiobjective Optimization," in *IEEE Access*, vol. 8, pp. 183324-183343, **2020**, doi: 10.1109/ACCESS.2020.3029321.

[27] Xi Chen, Jianghai Xu, Ye Fang, Wenbin Li, Yuejiao Ding, Zhongmin Wan, Xiaodong Wang, Zhengkai Tu, Temperature and humidity management of PEM fuel cell power system using multi-input and multi-output fuzzy method, Applied Thermal Engineering, Volume 203, **2022**, 117865, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2021.117865. (https://www.sciencedirect.com/science/article/pii/S1359431121012898)

[28] Xi Chen, Jianghai Xu, Qian Liu, Yao Chen, Xiaodong Wang, Wenbin Li, Yuejiao Ding, Zhongmin Wan, Active disturbance rejection control strategy applied to cathode humidity control in PEMFC system, Energy Conversion and Management, Volume 224, **2020**, 113389, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2020.113389. (https://www.sciencedirect.com/science/article/pii/S0196890420309250)

[29] Luo Yang, Nik-Nazri Nik-Ghazali, Mohammed A.H. Ali, Wen Tong Chong, Zhenzhong Yang, Haichao Liu, A review on thermal management in proton exchange membrane fuel cells: Temperature distribution and control, Renewable and Sustainable Energy Reviews, Volume 187, **2023**, 113737, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2023.113737. (https://www.sciencedirect.com/science/article/pii/S1364032123005944)

[30] Jiamin Xu, Caizhi Zhang, Zhongmin Wan, Xi Chen, Siew Hwa Chan, Zhengkai Tu, Progress and perspectives of integrated thermal management systems in PEM fuel cell vehicles: A review, Renewable and Sustainable Energy Reviews, Volume 155, **2022**, 111908, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.111908. (https://www.sciencedirect.com/science/article/pii/S1364032121011746)

[31] Junjie Zhao, Zhengkai Tu, Siew Hwa Chan, In-situ measurement of humidity distribution and its effect on the performance of a proton exchange membrane fuel cell, Energy, Volume 239, Part D, **2022**, 122270, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.122270. (https://www.sciencedirect.com/science/article/pii/S0360544221025184)

[32] Zhutian Xu, Diankai Qiu, Peiyun Yi, Linfa Peng, Xinmin Lai, Towards mass applications: A review on the challenges and developments in metallic bipolar plates for PEMFC, Progress in Natural Science: Materials International, Volume 30, Issue 6, **2020**, Pages 815-824, ISSN 1002-0071, https://doi.org/10.1016/j.pnsc.2020.10.015. (https://www.sciencedirect.com/science/article/pii/S100200712030544X)

[33] Xi Chen, Fasen Chai, Shenglin Hu, Jingying Tan, Liang Luo, Huahui Xie, Zhongmin Wan, Zhiguo Qu, Design of PEMFC bipolar plate cooling flow field based on fractal theory, Energy Conversion and Management: X, Volume 20, **2023**, 100445, ISSN 2590-1745, https://doi.org/10.1016/j.ecmx.2023.100445. (https://www.sciencedirect.com/science/article/pii/S2590174523001010)

[34] C.W. Wu, W. Zhang, X. Han, Y.X. Zhang, G.J. Ma, A systematic review for structure optimization and clamping load design of large proton exchange membrane fuel cell stack, Journal of Power Sources, Volume 476, **2020**, 228724, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2020.228724. (https://www.sciencedirect.com/science/article/pii/S0378775320310284)

[35] Diankai Qiu, Linfa Peng, Peiyun Yi, Werner Lehnert, Xinmin Lai, Review on proton exchange membrane fuel cell stack assembly: Quality evaluation, assembly method, contact behavior and process design, Renewable and Sustainable Energy Reviews, Volume 152, **2021**, 111660, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.111660. (https://www.sciencedirect.com/science/article/pii/S1364032121009357)

[36] Su Zhou, Lei Fan, Gang Zhang, Jianhua Gao, Yanda Lu, Peng Zhao, Chaokai Wen, Lin Shi, Zhe Hu, A review on proton exchange membrane multi-stack fuel cell systems: architecture, performance, and power management, Applied Energy, Volume 310, **2022**, 118555, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2022.118555. (https://www.sciencedirect.com/science/article/pii/S0306261922000411)

[37] Xiaohui Yan, Chen Lin, Zhifeng Zheng, Junren Chen, Guanghua Wei, Junliang Zhang, Effect of clamping pressure on liquid-cooled PEMFC stack performance considering inhomogeneous gas diffusion layer compression, Applied Energy, Volume 258, **2020**, 114073, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2019.114073. (https://www.sciencedirect.com/science/article/pii/S030626191931760X)

[38] Lixin Fan, Zhengkai Tu, Siew Hwa Chan, Recent development in design a state-of-art proton exchange membrane fuel cell from stack to system: Theory, integration and prospective, International Journal of Hydrogen Energy, Volume 48, Issue 21, **2023**, Pages 7828-7865, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2022.11.212. (https://www.sciencedirect.com/science/article/pii/S0360319922055306)

[39] Jiquan Han, Jianmei Feng, Ping Chen, Yunmei Liu, Xueyuan Peng, A review of key components of hydrogen recirculation subsystem for fuel cell vehicles, Energy Conversion and Management: X, Volume 15, **2022**, 100265, ISSN 2590-1745, https://doi.org/10.1016/j.ecmx.2022.100265. (https://www.sciencedirect.com/science/article/pii/S2590174522000885)

[40] Xuhui Wang, Yikang Lu, Baitao Zhang, Jinling Liu, Sichuan Xu, Experimental analysis of an ejector for anode recirculation in a 10 kW polymer electrolyte membrane fuel cell system, International Journal of Hydrogen Energy, Volume 47, Issue 3, **2022**, Pages 1925-1939, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2021.10.140. (https://www.sciencedirect.com/science/article/pii/S0360319921041719)

[41] Anchasa Pramuanjaroenkij, Sadık Kakaç, The fuel cell electric vehicles: The highlight review, International Journal of Hydrogen Energy, Volume 48, Issue 25, **2023**, Pages 9401-9425, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2022.11.103. (https://www.sciencedirect.com/science/article/pii/S0360319922053368)

[42] Jiamin Xu, Caizhi Zhang, Ruijia Fan, Huanhuan Bao, Yi Wang, Shulong Huang, Cheng Siong Chin, Congxin Li, Modelling and control of vehicle integrated thermal management system of PEM fuel cell vehicle, Energy, Volume 199, **2020**, 117495, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2020.117495. (https://www.sciencedirect.com/science/article/pii/S0360544220306022)

[43] Yuanyang Zhao, Yunxia Liu, Guangbin Liu, Qichao Yang, Liansheng Li & Zhicheng Gao (**2022**) Air and hydrogen supply systems and equipment for PEM fuel cells: a review, International Journal of Green Energy, 19:4, 331-348, DOI: 10.1080/15435075.2021.1946812 (https://www.tandfonline.com/doi/full/10.1080/15435075.2021.1946812)

Sources
Research areas of PEMFC for mobile applications

Karlsruhe Institute of Technology

[51] Tiankuo Chu, Meng Xie, Yue Yu, Baoyun Wang, Daijun Yang, Bing Li, Pingwen Ming, Cunman Zhang, Experimental study of the influence of dynamic load cycle and operating parameters on the durability of PEMFC, Energy, Volume 239, Part D, **2022**, 122356, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.122356. (https://www.sciencedirect.com/science/article/pii/S0360544221026050)

[52] Pengcheng Liu, Sichuan Xu, Jiaxing Fu, Can Liu, Experimental investigation on the voltage uniformity for a PEMFC stack with different dynamic loading strategies, International Journal of Hydrogen Energy, Volume 45, Issue 50, **2020**, Pages 26490-26500, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2020.05.070. (https://www.sciencedirect.com/science/article/pii/S0360319920318474)

[53] Zhiyang Liu, Jian Chen, Hao Liu, Chizhou Yan, Yang Hou, Qinggang He, Jiujun Zhang, Daniel Hissel, Anode purge management for hydrogen utilization and stack durability improvement of PEM fuel cell systems, Applied Energy, Volume 275, **2020**, 115110, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2020.115110. (https://www.sciencedirect.com/science/article/pii/S030626192030622X)

[54] Homayoon Kanani, Mehrzad Shams, Mohammadreza Hasheminasab, Ali Bozorgnezhad, Model development and optimization of operating conditions to maximize PEMFC performance by response surface methodology, Energy Conversion and Management, Volume 93, **2015**, Pages 9-22, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2014.12.093. (https://www.sciencedirect.com/science/article/pii/S019689041401142X)

[55] Yuan Gao, Mengzhu Lin, Research on the performance characteristics of hydrogen circulation pumps for PEMFC vehicles, International Journal of Hydrogen Energy, Volume 50, Part C, **2024**, Pages 1255-1272, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2023.10.248. (https://www.sciencedirect.com/science/article/pii/S036031992305396X)

[56] Tabbi Wilberforce, A.G. Olabi, Hegazy Rezk, Almoataz Y. Abdelaziz, Mohammad Ali Abdelkareem, Enas Taha Sayed, Boosting the output power of PEM fuel cells by identifying best-operating conditions, Energy Conversion and Management, Volume 270, **2022**, 116205, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2022.116205. (https://www.sciencedirect.com/science/article/pii/S0196890422009827)

[57] Junbo Hou, Min Yang, Changchun Ke, Junliang Zhang, Control logics and strategies for air supply in PEM fuel cell engines, Applied Energy, Volume 269, **2020**, 115059, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2020.115059. (https://www.sciencedirect.com/science/article/pii/S0306261920305717)

[58] Ze Liu, Baitao Zhang, Sichuan Xu, Research on air mass flow-pressure combined control and dynamic performance of fuel cell system for vehicles application, Applied Energy, Volume 309, **2022**, 118446, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2021.118446. (https://www.sciencedirect.com/science/article/pii/S0306261921016718)

[59] Hanqing Wang, Simon Morando, Arnaud Gaillard, Daniel Hissel, Sensor development and optimization for a proton exchange membrane fuel cell system in automotive applications, Journal of Power Sources, Volume 487, **2021**, 229415, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2020.229415. (https://www.sciencedirect.com/science/article/pii/S0378775320316992)

[60] Diankai Qiu, Xiangyang Zhou, Minxue Chen, Zhutian Xu, Linfa Peng, Optimization of control strategy for air-cooled PEMFC based on in-situ observation of internal reaction state, Applied Energy, Volume 350, **2023**, 121752, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2023.121752. (https://www.sciencedirect.com/science/article/pii/S0306261923011169)

[61] Hwanyeong Oh, Yoon-Young Choi, Minjin Kim, Young-Jun Sohn, Seung-Gon Kim, Won-Yong Lee, Experimental validation of passive and active fault-tolerant controls against sensor faults in a proton exchange membrane fuel cell system, Journal of Process Control, Volume 129, **2023**, 103064, ISSN 0959-1524, https://doi.org/10.1016/j.jprocont.2023.103064. (https://www.sciencedirect.com/science/article/pii/S0959152423001518)

[62] J. Aubry, N. Yousfi Steiner, S. Morando, N. Zerhouni, D. Hissel, Fuel cell diagnosis methods for embedded automotive applications, Energy Reports, Volume 8, **2022**, Pages 6687-6706, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2022.05.036. (https://www.sciencedirect.com/science/article/pii/S2352484722008824)

Sources

Model of the architecture of the validation configurations – IPEK XiL

[1] https://www.e-motec.net/making-fuel-cells-more-durable-and-affordable
[2] https://www.semanticscholar.org/paper/Reduction-of-hydrogen-transfer-by-constrained-of-in-Ebadighajari-Vaal/90ff8cf42b91e63c0d8bc77d746013fd1e8220ae
[3] https://www.mdpi.com/1996-1073/12/19/3692