Contents of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06: Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Coordinator of the WP

Czech Technical University in Prague, Faculty of Mechanical Engineering, Prof. Ing. Jan Macek, DrSc.

Participants of the WP

Charles University, Faculty of Mathematics and Physics, Prof. Mgr. Iva Matolínová, Dr., ŠKODA AUTO a. s. Dr. Ing. M. Hrdlička, MBA, Brano a. s., Ing. Pavel Juříček, PhD.

Main Goal of the WP

The current WP considers powertrains and components in fuel cell design and implementation in vehicles together with ICE for renewable fuels, hybrid drives and emerging markets and moreover Heating, Ventilation and Air Conditioning systems .

In the former item, experiments and simulations are focused on air- and hydrogen loops including pressure boosting and hydrogen storage aiming at increase of a FC power density without too significant reduction of efficiency. Bipolar plate materials and design are investigated at specimens trying to find light and corrosion resistive materials with sufficient shape variability. In the latter item, an optimization of HVAC for powertrains with low waste-heat sources and needs for intensive cooling (e.g., during battery charging) is done. Heating and cooling is realized by switching flow using the same components in HVAC circuit. Different refrigerants/heating media are under investigation. **The main goal is the use of CO_2-neutral energy sources for vehicle powertrains, optimized according to their purpose.**

Deliverables of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Obligatory 4-WP06 Deliverables:

4-WP06-001: Simulation of highly humid air expansion R-software CTU FME+UK MFF

4-WP06-002: Hydrogen recirculation ejector for PEM FC Fuzit-Registered model (Užitný vzor) CTU FME

4-WP06-005: Short FC stack with opened cathode Gfunk-Functional specimen (funkční vzorek) CU MFF+CTU FME

4-WP06-007: Tools for design and control of hydrogen production unit R-software CTU FME+Brano

4-WP06-008: Model of advanced HVAC systems for BEV and PHEV R-software CTU FME+Škoda Auto

4-WP06-010: Tools for local optimization of selected HVAC layouts during trip realization. R-software CTU FME+Škoda Auto

Deliverables of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Obligatory 4-WP06 Deliverables of "Other Results" type:

4-WP06-003: Auxiliary air-loop device for using pressurized air exhaust at PEM FCs with electrically driven air compressor CTU FME+UK MFF

4-WP06-004: Analysis of possibilities for using expanded air at air-loop outlet for FC cooling CTU FME+ CU FMP

4-WP06-006: Bipolar plates with opened cathode CU FMP+CTU FME

4-WP06-009: Layouts of HVAC systems for BEVs and PHEVs. CTU FME+Škoda Auto

Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

	Time plan and list of activities in FEFEFOV 4 – WP 06	Coordinator of Activity	Year			
			2023	2024	2025	2026
001	4-WP6-001Simulation of highly humid air expansion	Jan Macek, CTU FME	YES	YES	No	No
002	4-WP6-002 Hydrogen side recirculation ejector design and description for patent	Jan Macek, CTU FME	YES	YES	YES	No
003	4-WP6-003 and 004 Pressure boosting of PEM FC at air-loop side (2025) and cooling (2024)	Jan Macek, CTU FME	YES	YES	YES	No
004	4-WP06-005 and 006 Design and realization of short stack with three 100cm2 fuel cells with opened cathode on the base of carbon material	Iva Matolínová, UK MFF	YES	YES	YES	No
005	4-WP6-007 Simulations of power requirements and pressure cylinder filling process for design of H2 production unit.	Jan Macek, CTU FME	No	YES	YES	No
006	4-WP06-008 and 009 Possible HVAC system layouts with heat pump for BEV/PHEV	Jan Macek, CTU FME	YES	YES	No	No
007	4-WP6-010 Optimization of HVAC system layouts with heat pump for BEV/PHEV based on implementation into vehicle models including trip control	Jan Macek, CTU FME	No	No	YES	No

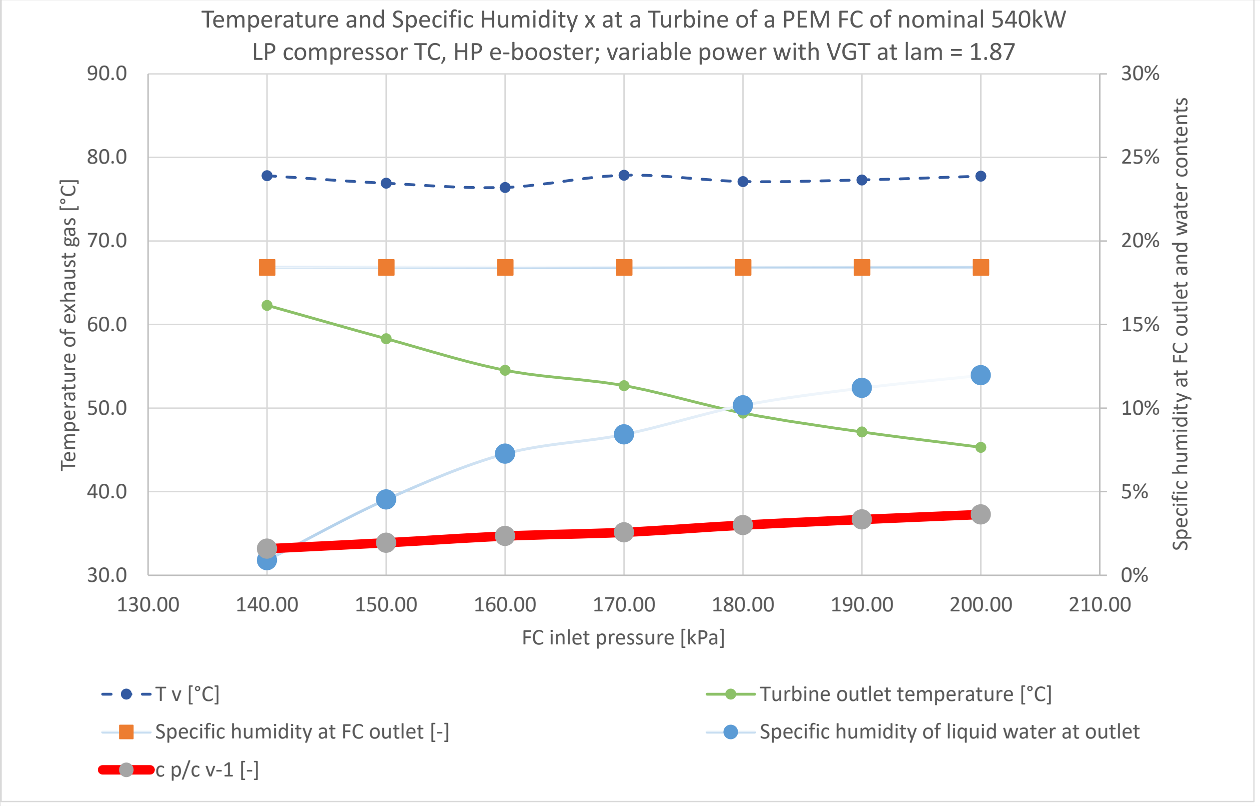
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-001: Simulation of highly humid air expansion

Algorithm and de-bugging for final code elaboration in MS Excel:

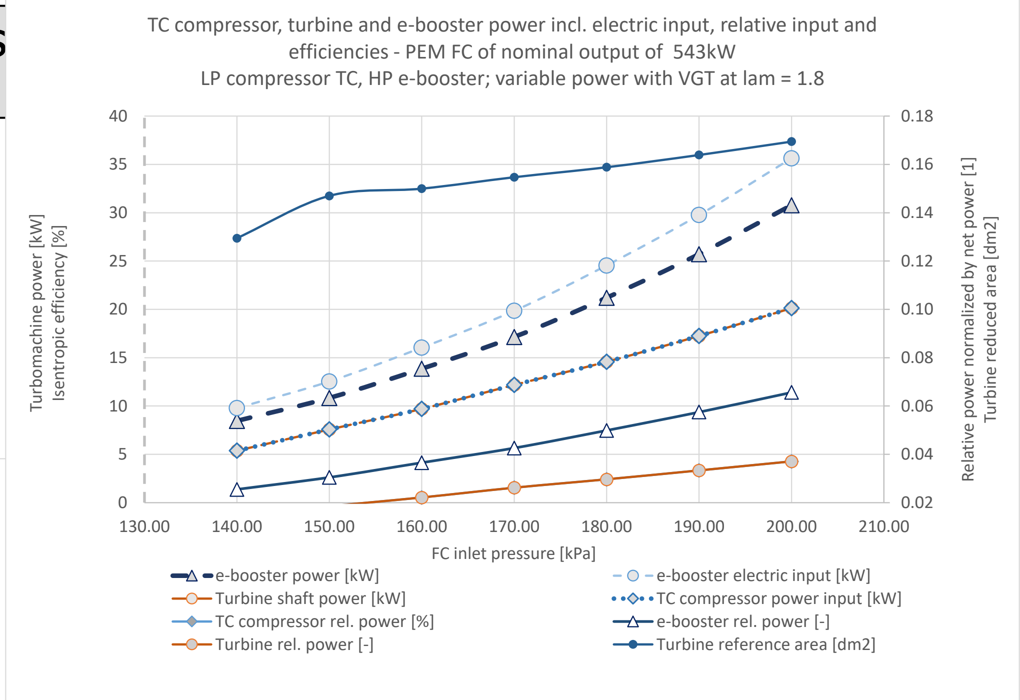
- analysis of possible approaches to two-phase expansion with irreversibility and implementation of isentropic efficiency definition
- concept of averaged c p/c v exponent (c p/c v – 1 in graphs)
- combined Newton-Raphson and simple iteration for solving of set of algebraic equations
- test of convergence
- additional improvement possibilities for future development based on entropy calculation

- use of c p/c v surrogating mean isentropic exponent for isentropic expansion prediction including water condensation – sufficient for low pressure ratio expansion of humid exhaust gas.



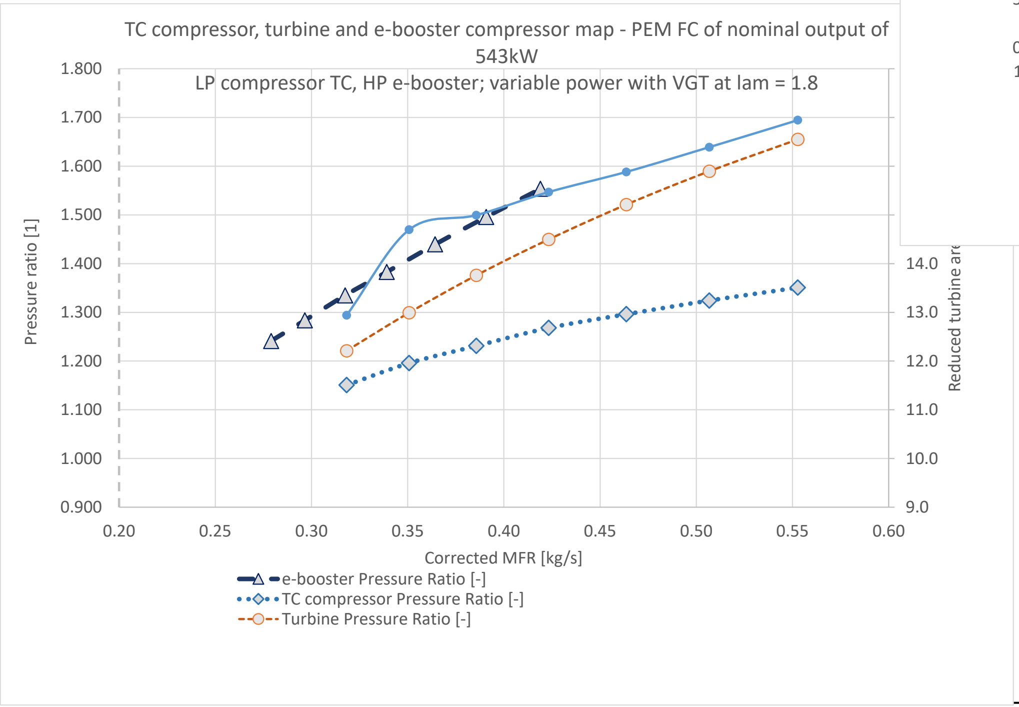
Activities of Work Package 4-WP06 Alternative Fueled Powertrains
Future Vehicles: Fuel Cells and Energy Management

4-WP04-001: Simulation of highly humid air expansion



The first results of turbocharger matching to high-power PEM FC and its control:

- compressor data in the form of compressor map
- VTG turbine area
- turbine power and normalized power relative to PEM FC nominal power



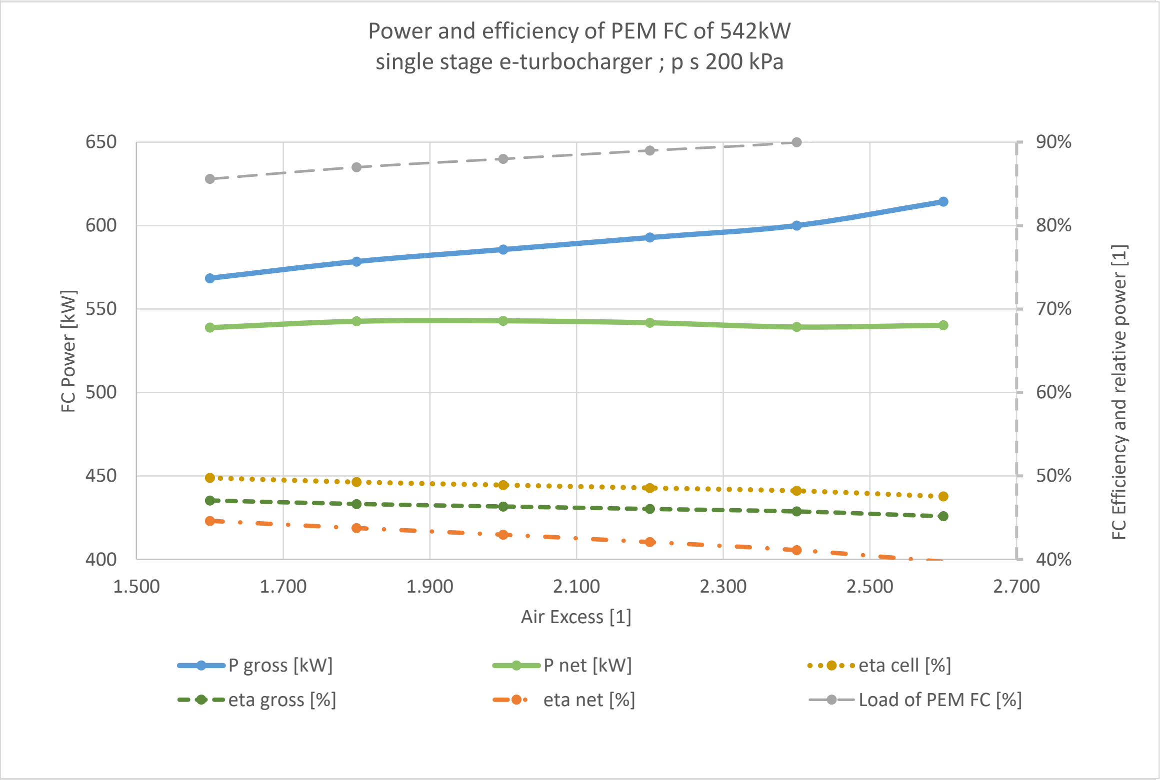
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-001: Simulation of highly humid air expansion

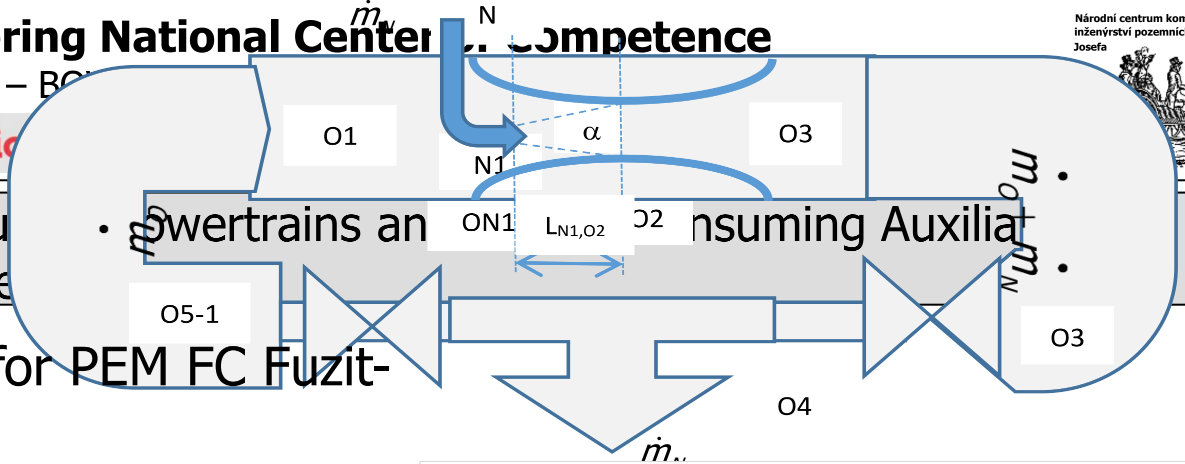
The first results of turbocharger layout features for high-power PEM fuel cell (FC).

Comparison of "natural aspiration" with a booster, covering internal pressure loss of air-side loop only, e-booster + turbocharger (both high-pressure HP and low-pressure LP positions of an e-booster are equivalent if efficiency is considered) and single stage e-turbo. Boosted variants with FC inlet pressure ratio of 200 kPa:

- PEM FC gross and net powers
- gross power normalized by rated power of a fuel cell
- PEM FC efficiencies including e-booster or e-turbo



Activities of Work Package 4-WP06 Alternative Fu... ...owertrains an... ...nsuming Auxilia...
Future Vehicles: Fuel Cells and Energy Manageme...



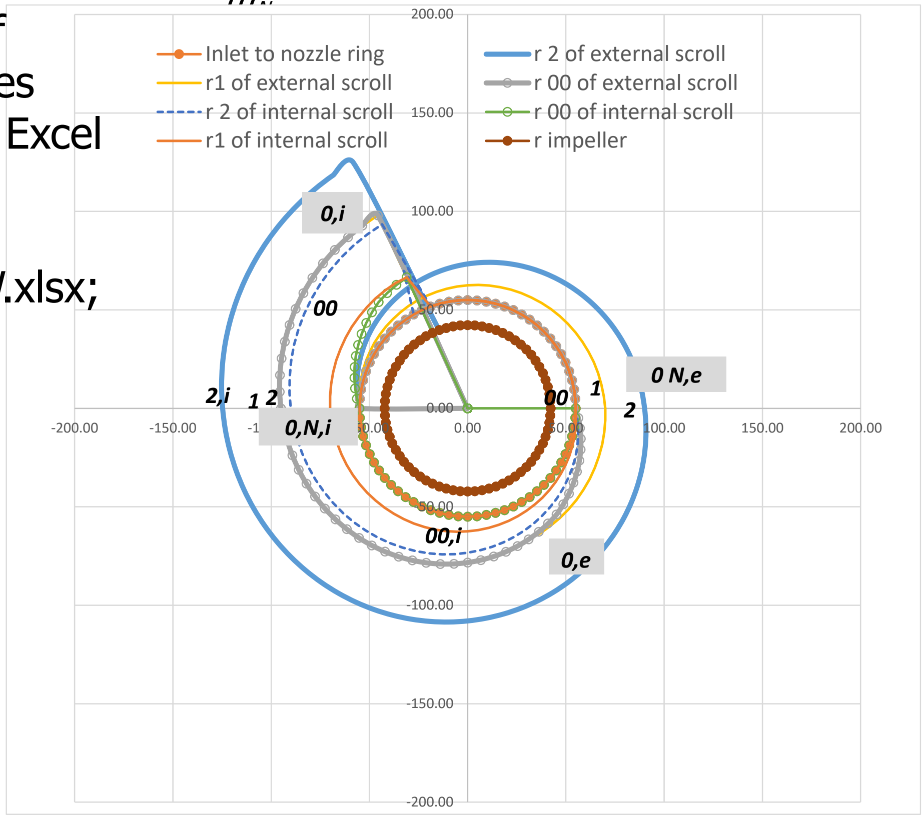
4-WP06-002: Hydrogen recirculation ejector for PEM FC Fuzit-Registered model (Užitný vzor)

Lay-out of Ejector Circuit

- O1 – acceleration to N1 – mixing to O2 – diffuser to O3 – pressure loss in small channels of an anode – hydrogen delivery to anode O5 with pressure loss against cathode base pressure – additional pressure loss/static pressure recovery to O5-1 – O1
- Additional diffuser effect of hydrogen leaving to FC anode is considered downstream of O4.
- Losses in pipe bends are added to wall friction losses.
- Pressure at the end of the circuit has to be at least equal to circulating gas inlet to a mixing chamber (acceleration of flow required for good ejector efficiency).

Selection and testing of suitable simulation codes already available in MS Excel

TURBO-v13_PEMFC_v11_30kW.xlsx; Ejector_v6.xslx; Inlet_scroll_v14.xlsx)



Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

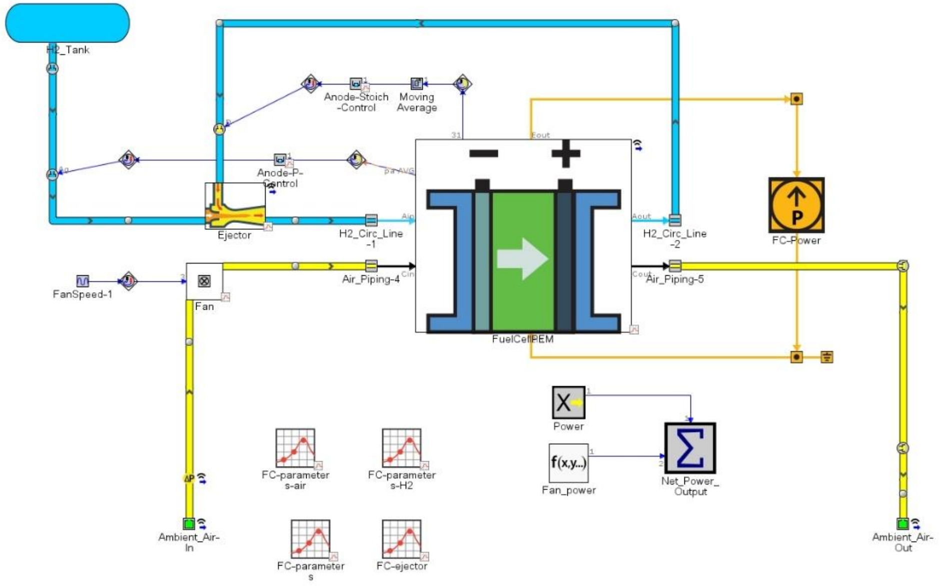
4-WP06-003: Auxiliary air-loop device for using pressurized air exhaust at PEM FCs with electrically driven air compressor

4-WP06-004: Analysis of possibilities for using expanded air at air-loop outlet for FC cooling

- Analysis of possible principles including COMPREX/HYPREX

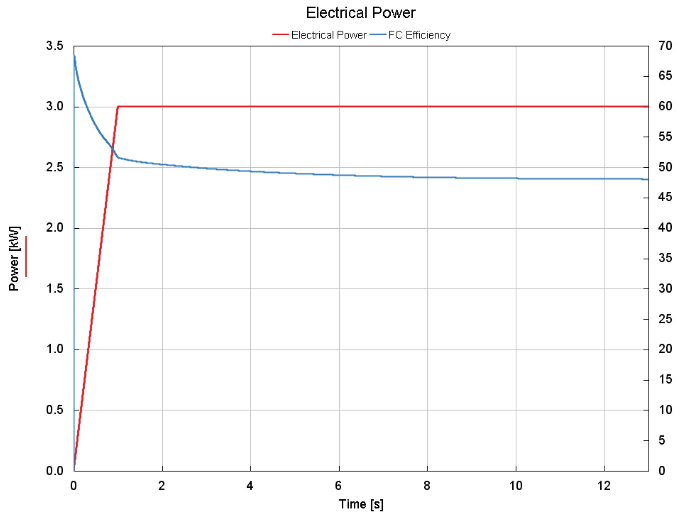
- Selection of simulation codes already available in MS Excel
- TURBO-v13_PEMFC_v11_30kW.xlsx;
- Ejector_v6.xslx;

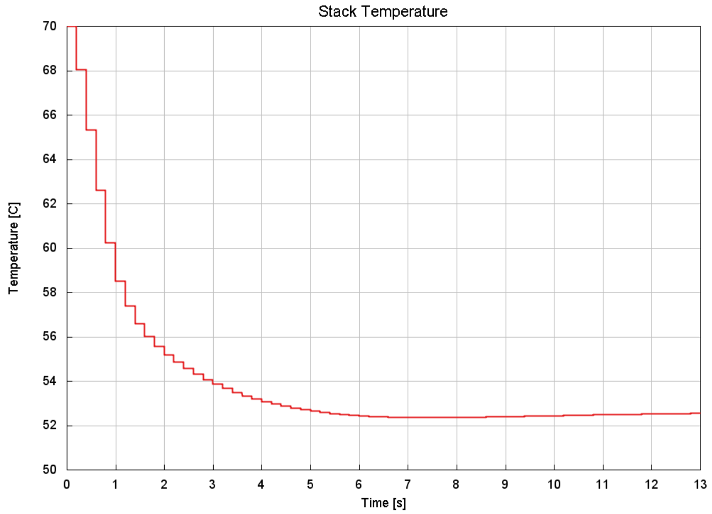
- Warming-up of humid gas with high water contents - cooling effect simulation
- Simulation tool GT Suite.

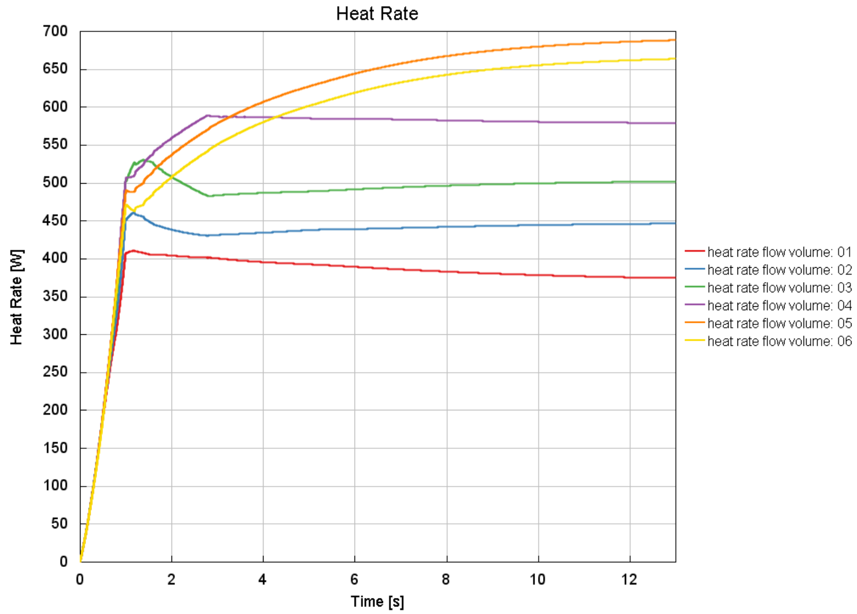


Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-003: Auxiliary air-loop device for using pressurized air exhaust at PEM FCs with electrically driven air compressor – examples of simulations



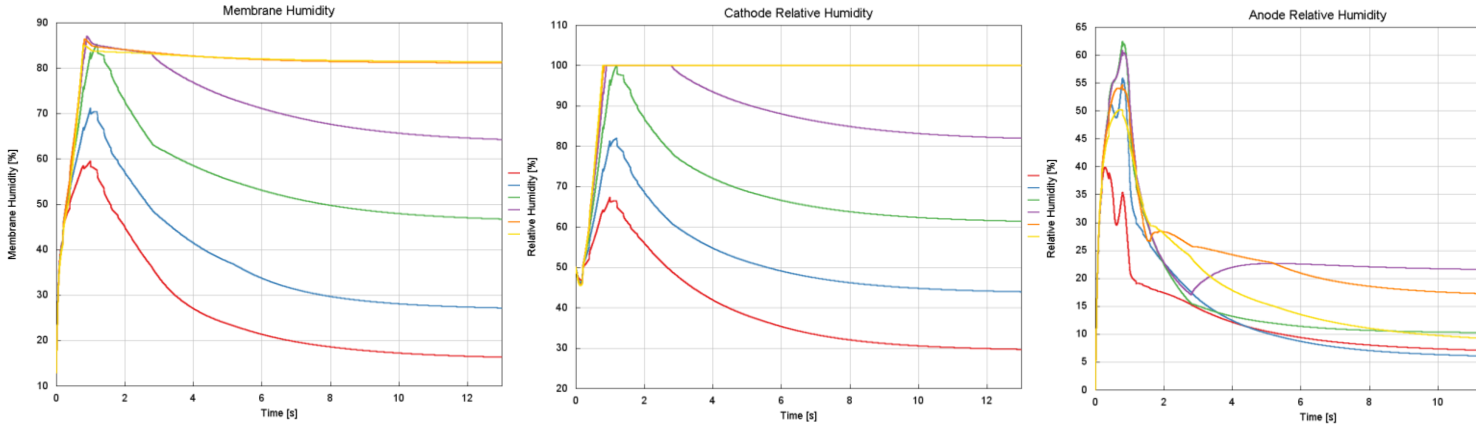




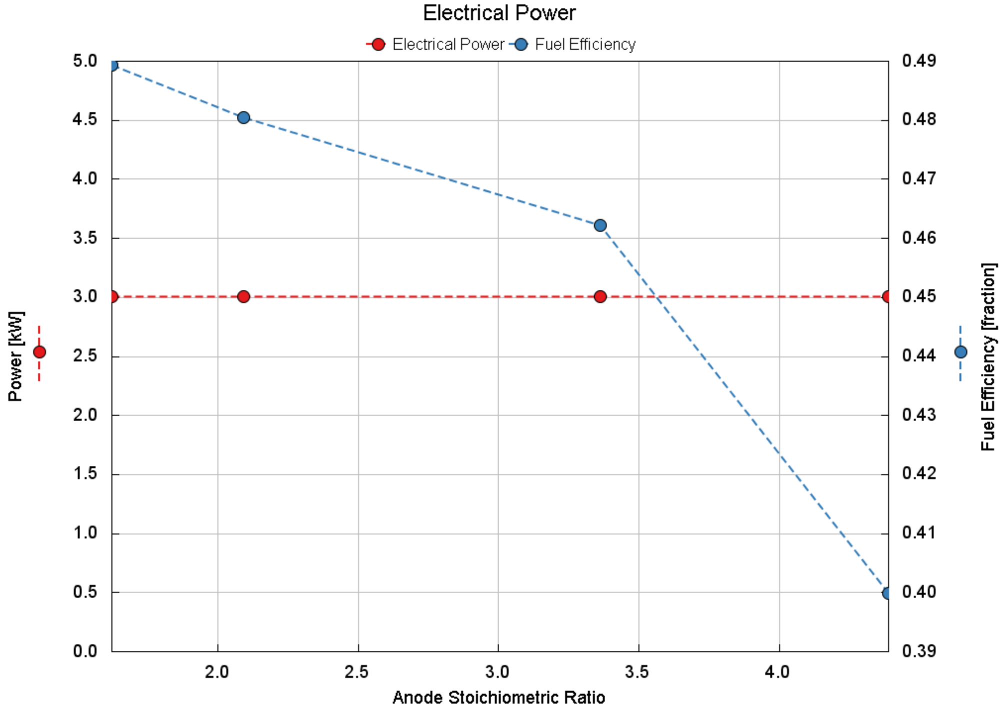
Transient results of PEM FC simulation in GT Suite: Electric power and FC efficiency during operation mode defined by anode stoichiometric ratio 1.3 and cathode stoichiometric ratio 2.1 in GT Suite

Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-003: Auxiliary air-loop device for using pressurized air exhaust at PEM FCs with electrically driven air compressor – examples of simulations



Transient results of PEM FC simulation: Membrane, anode and cathode humidity during operation mode defined by anode stoichiometric ratio 1.3 and cathode stoichiometric ratio 2.1.
Cathode is close to the source of water, anode should be humid in countercurrent way of water/protons fluxes, additionally, by hydrogen humification.

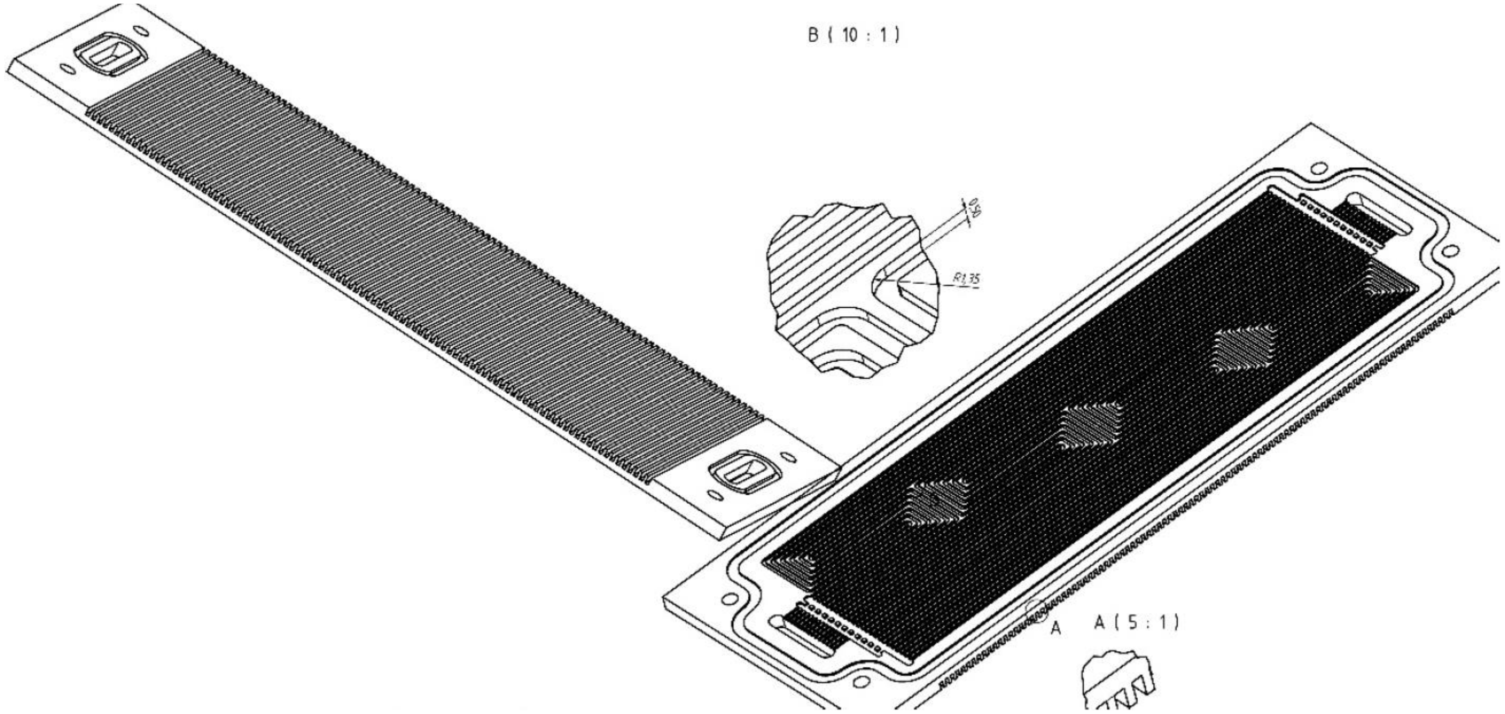


Impact of air flow (air excess) on open cathode FC power

Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-005 and 006 Design and realization of short stack with three 100cm2 fuel cells with opened cathode on the base of carbon material

- Material technology selection and design of bipolar plate specimens, manufacture of the first type and preliminary testing.
- Analyzes of possible solutions using Epoxy resin-nanographite composite materials.
- Paper on preliminary results.



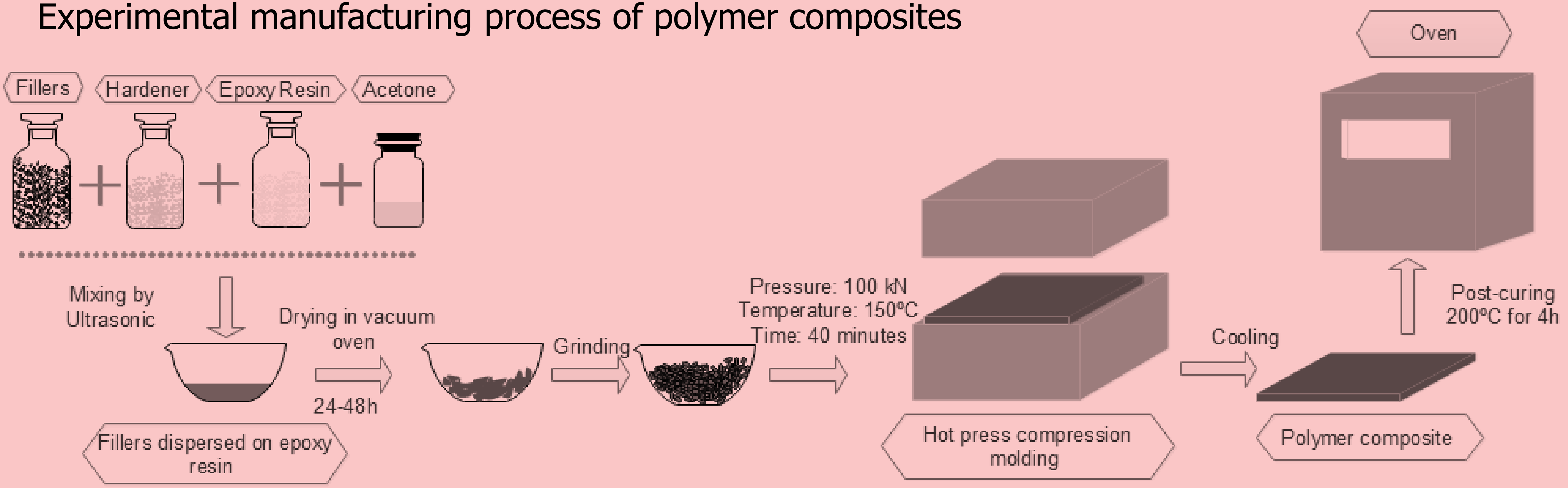
Graphite bipolar plate used in FC stack with straight air channels and serpentine hydrogen channels

Iva Matolínová – Presentation 4-WP 06 – 005 and 006

Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-005 and 006 Design and realization of short stack with three 100cm2 fuel cells with opened cathode on the base of carbon material

Experimental manufacturing process of polymer composites



Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-005 and 006 Design and realization of short stack with three 100cm2 fuel cells with opened cathode on the base of carbon material

Steps of the process

Study the kinetic reaction of polymers by DSC → Preparation of polymer composites → Characterization of polymer composites → Preparation of polymer composite bipolar plates → Test in the fuel cell station

Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite

- Polymer composites (laboratory scale)

- Fuel cell station's BPs

- Stack's BPs

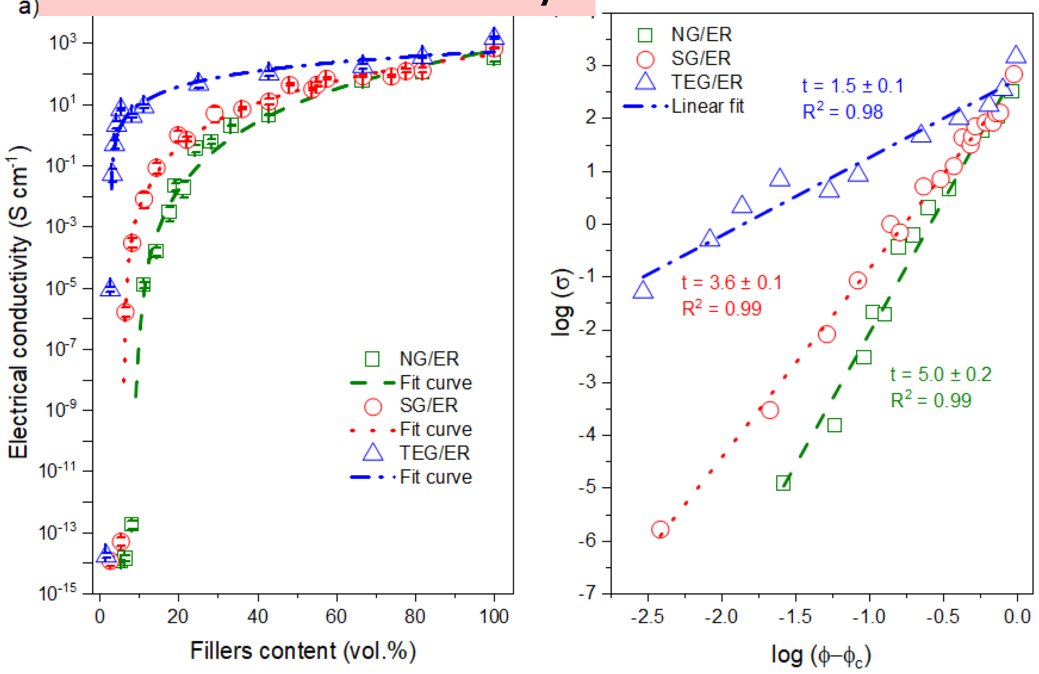
Fillers studied:

- commercially available natural graphite (NG)
- commercially available synthetic graphite (SG)
- own-prepared thermally expanded graphite (TEG)

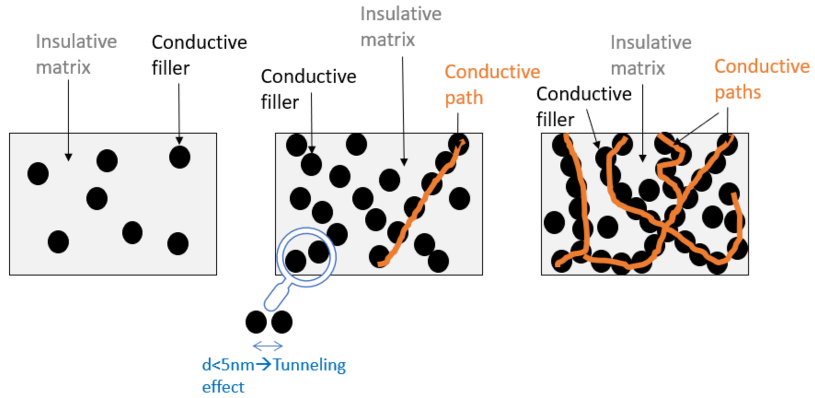
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Electrical conductivity

Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite



Composite system	Electrical percolation	
	ϕ_c (vol%)	t_{el}
NG/ER	8.5	5.0 ± 0.2
SG/ER	6	3.6 ± 0.1
TEG/ER	2.8	1.5 ± 0.1



Scaling law of the percolation model[1,2]

$$\sigma = \sigma_0 \cdot (\phi - \phi_c)^t$$

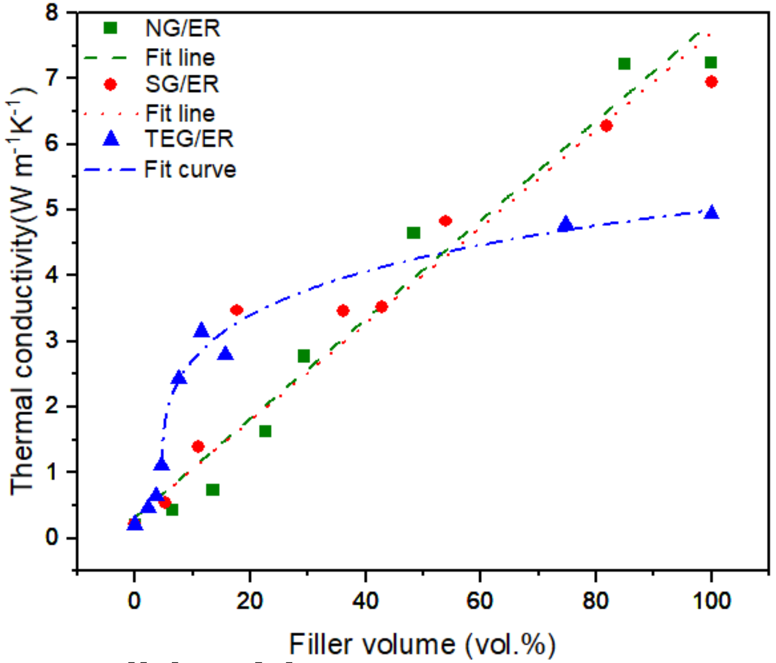
$$\log \sigma = \log \sigma_0 + t \cdot \log(\phi - \phi_c)$$

where **σ** is the composite conductivity, $\boldsymbol{\sigma_0}$ is theoretical filler conductivity, **ϕ** is filler volume fraction, $\boldsymbol{\phi_c}$ is the critical filler volume fraction, **t** is the critical index of conductivity.

[1] S. Kirkpatrick, *Rev. Mod. Phys*, (1973).
[2] R. Zallen,"The Physics of Amorphous Solids" (1983).

Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Thermal conductivity analysis



Parallel model $$\lambda = \phi\lambda_f + (1-\phi)\lambda_m$$

Percolation model $$\lambda = (1-\phi)\lambda_m + \lambda_f\left(\frac{\phi-\phi_c}{1-\phi_c}\right)^t$$

Where **ϕ** is filler volume fraction, **ϕ_c** is the critical volume fraction
t is the critical index, **λ_f** is the filler thermal conductivity, **λ_m** is the matrix thermal conductivity

Linear fitting

- Based on the parallel model[3]
- The phonons are transported by conductive layers.

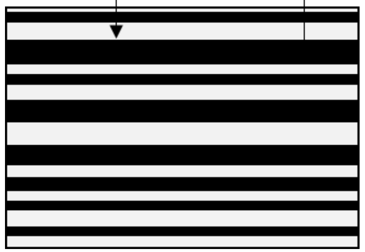
[3] *Appl. Phys. Rev. 9, 041403 (2022)*

Exponential fitting

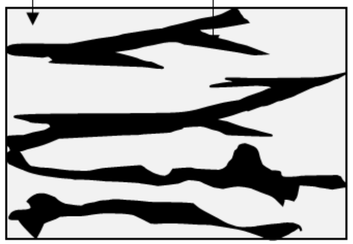
- Based on the percolation model[3]
- ϕ_c (vol%) = 5.1
  t_{th} = 0.12
- The phonons are transported between conductive particles

Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite

Insulative matrix
Conductive layer

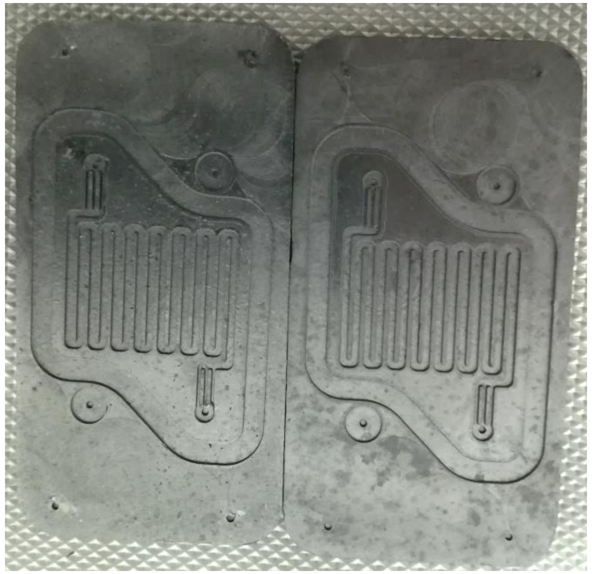


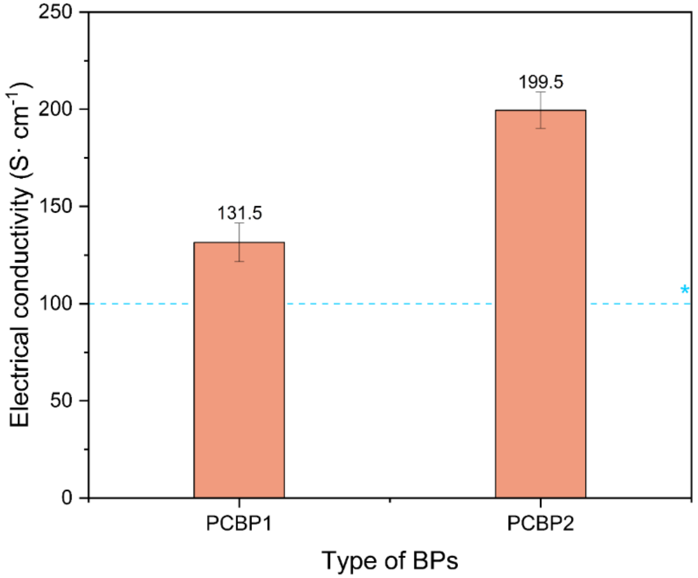
Insulative matrix
Conductive fillers



Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

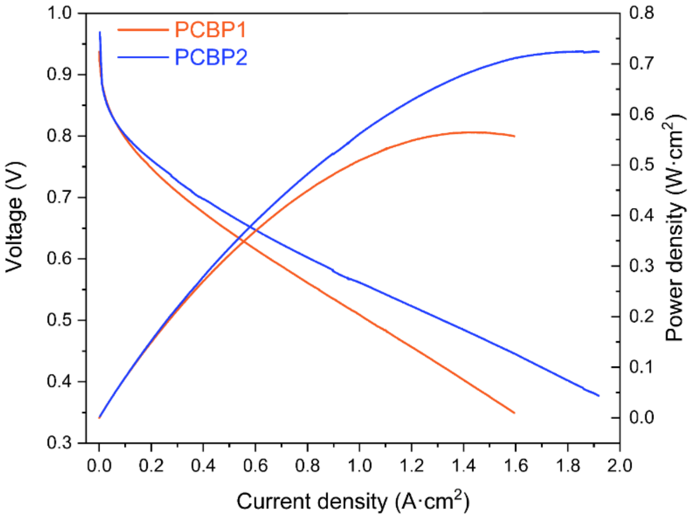
Polymer composite bipolar plates for single fuel cell





Electrical conductivity

Electrical conductivity effect on PEM fuel cell performance



Dimensions: 7.2 x 3 cm
Thickness: 2 - 2.5 mm
Composition: 90% filler + 10% Epoxy resin
Active surface area: 5 cm^2
PCBP1: Filler NG
PCBP2: Filler SG + TEG

Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite

Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Properties of BPs for PEM FCs

Characteristics	Units	DOE Target 2025[4]	Our work[5] (90 wt% fillers)
Electrical conductivity	S/cm	>100	>100
Flexural strength	MPa	>25	58
Tensile strength	MPa	>40	20
Compressive strength	MPa	50	-
Plate H_2 permeation coefficient	Std $cm^3/(sec\ cm^2 Pa)$ at 80°C, 3 atm, 100% RH	$2 \cdot 10^{-6}$	$6.1 \cdot 10^{-12}$
Corrosion, anode	$\mu A/cm^2$	<1	-
Corrosion cathode	$\mu A/cm^2$	<1	-

Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite

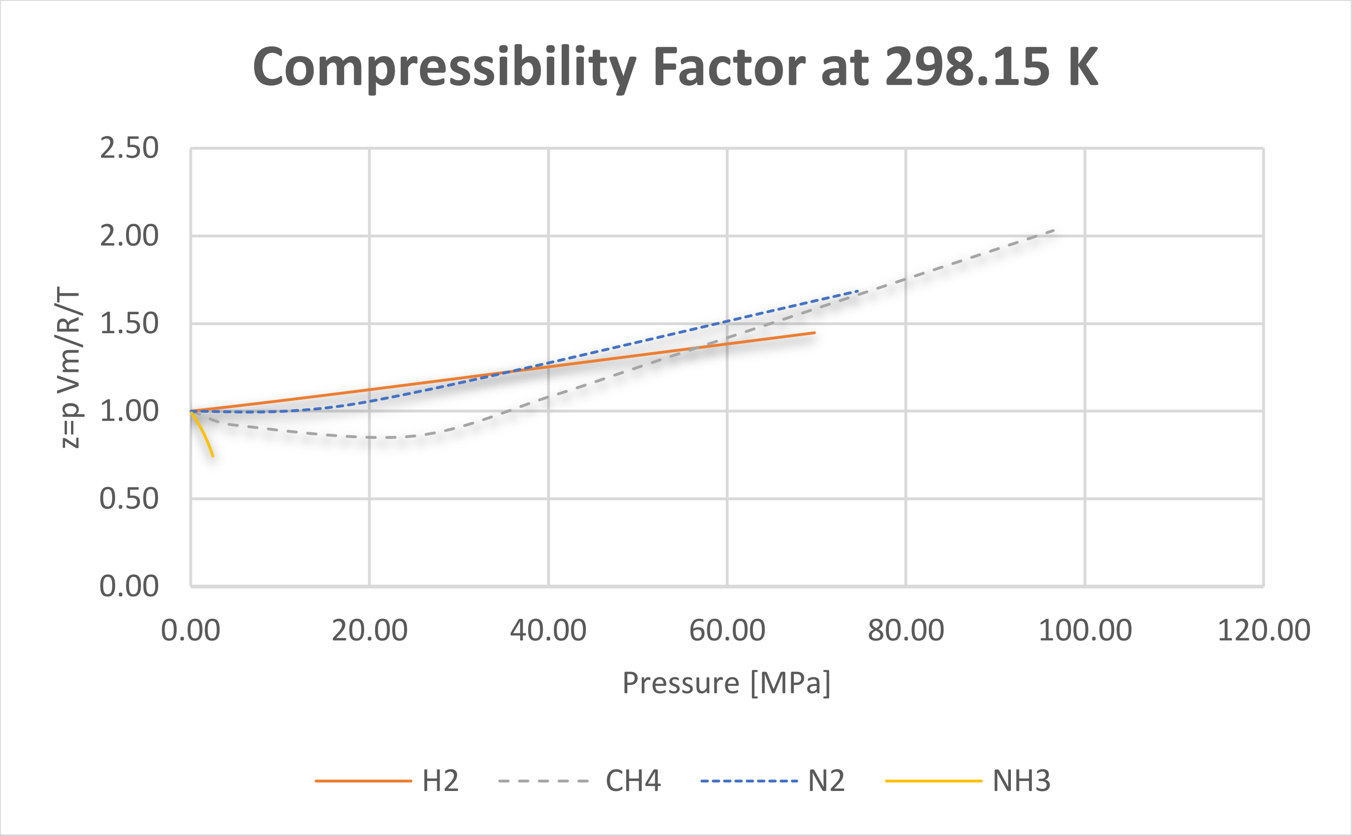
4 *DOE's 2020 technical and cost targets for bipolar plates*

5 *Effect of graphite fillers on electrical and thermal conductivity in epoxy-based composites: Percolation behavior and analysis. By: A.M. Darabut, Y. Lobko, Y. Yakovlev, M.G. Rodríguez; P. Levinský, T.N. Dinhová; L.B. Redondo, V. Kopecký, A. Farkas, D. Drozdenko, V. Matolín, I. Matolínová, Composites Science and Technology, submitted 4. 10. 2023*

Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP6-007 Simulations of power requirements and pressure cylinder filling process for design of H2 production unit

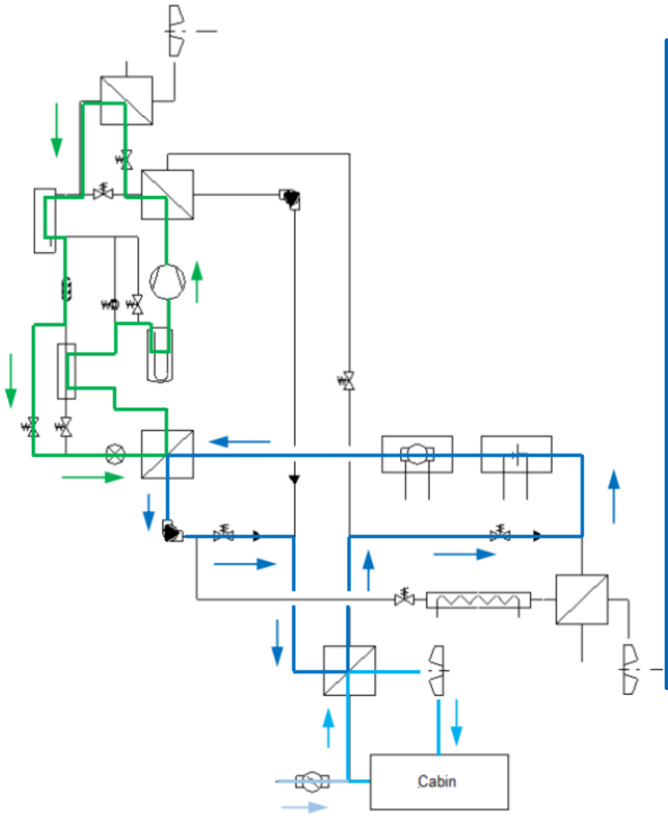
- Simulations of power requirements and pressure cylinder filling process for design of H2 production unit – physical bases for a model
- Programming of real gas features using BWR and Redlich Kwong equations of state BWR_v2.xslx inc. Joule-Thompson coefficient and real work for compression

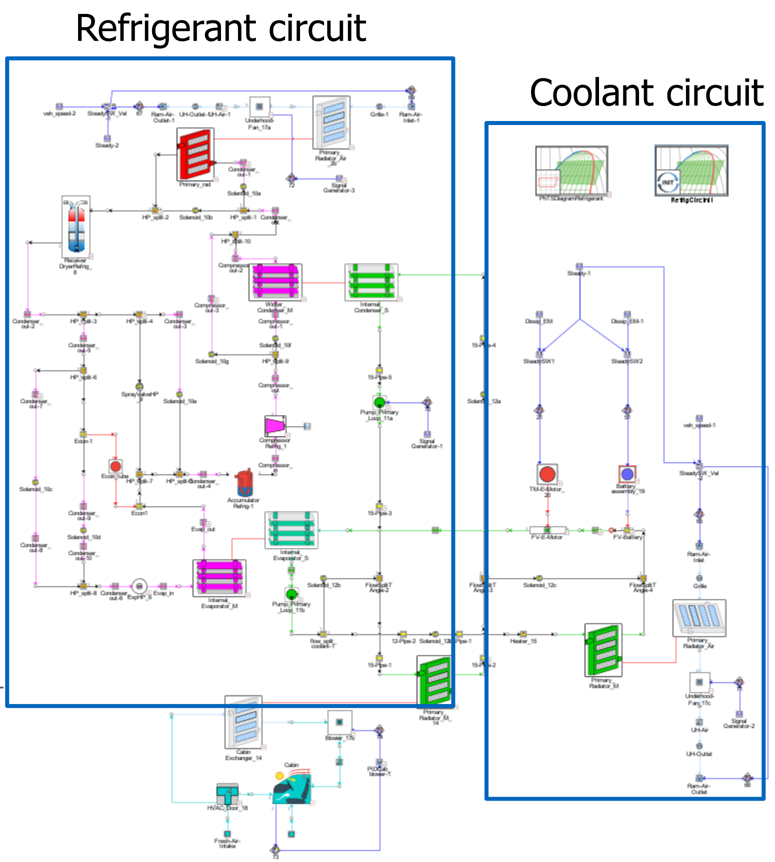


Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-008: Model of advanced HVAC systems for BEV and PHEV

- elaboration of typical layout of system for starting simulation
- construction of a model for simulation in GTS
- Two designs for HVAC and cooling systems of different complexity were proposed in the form of basic scheme of powertrain cooling and heat pump HVAC system for a battery EV or PHEV. Newly developed code for preliminary design of HVAC group was used as boundary condition. The preliminary designs have been fitted for two real systems, using collaboration with Skoda Auto.

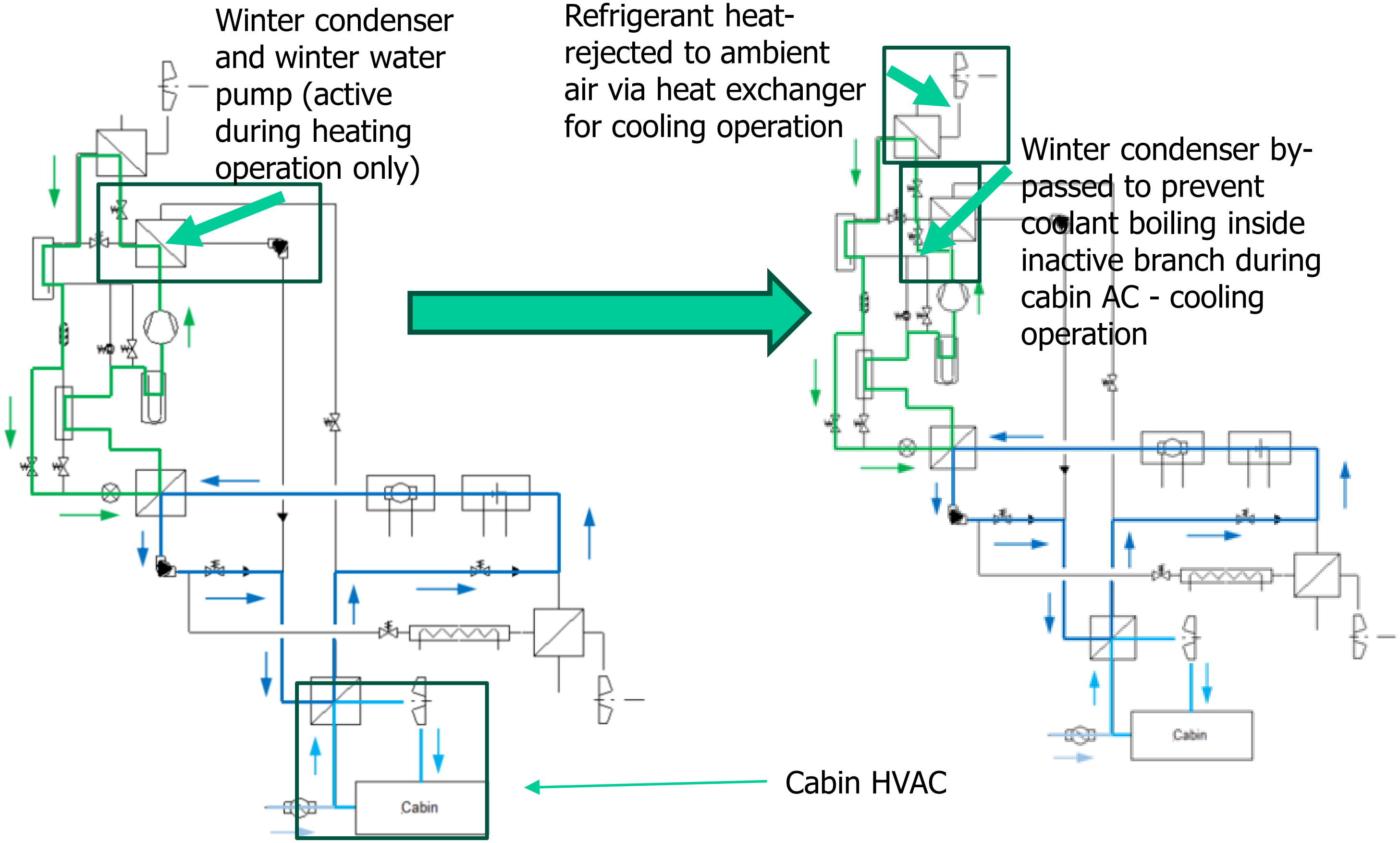




Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-008: Model of advanced HVAC systems for BEV and PHEV

- Basic layout for organic fluid system with possible switching between AC/heating and forced cooling of a battery during charging designed and transformed to GTS scheme
- Assessment of validity of the first results for heating and AC cooling – cabin and e-motor/battery circuit
- Updating the scheme due to found issues during AC function of a circuit.



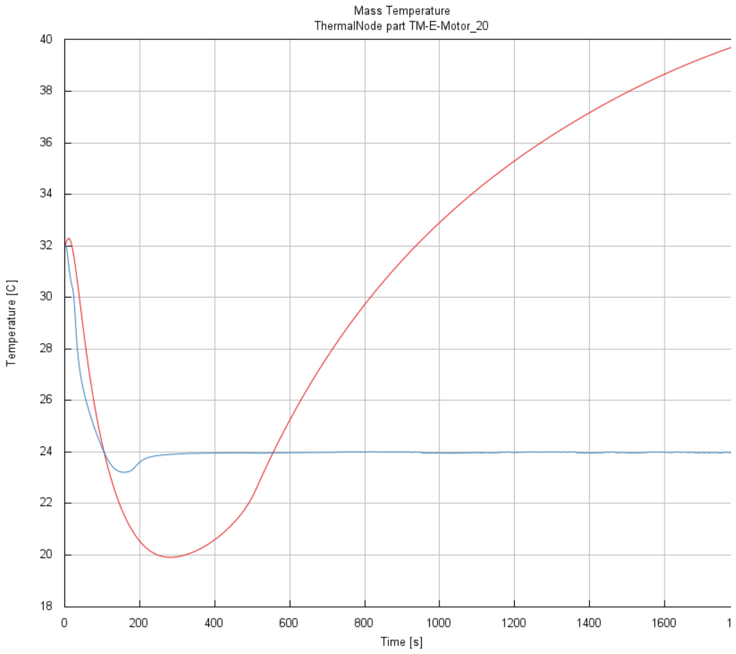
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-008: Model of advanced HVAC systems for BEV and PHEV

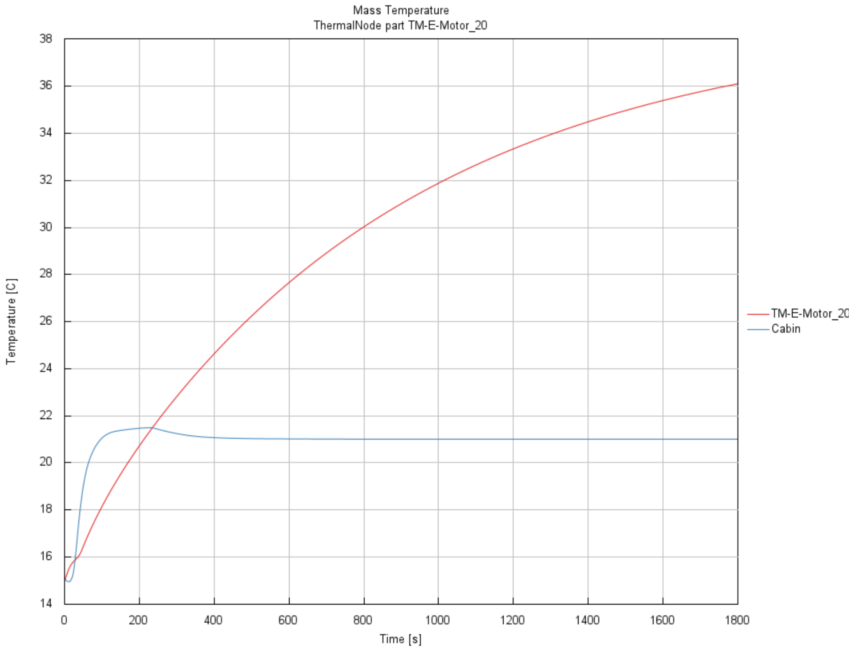
- Operation during cabin and electric powertrain cooling - left. Before change to heating mode is done, the "summer" condenser has to be evacuated.
- Operation during cabin heating, using waste heat from electric powertrain and heat from ambient air - right.
- Thaw temporary mode for ice removal from inlet heat exchanger is prepared to simulation, as well.

Results of system response during static car driving (constant velocity – 50 km/h)

Cooling&AC – outside temperature 32 degC



Heating of cabin – outside -2 degC

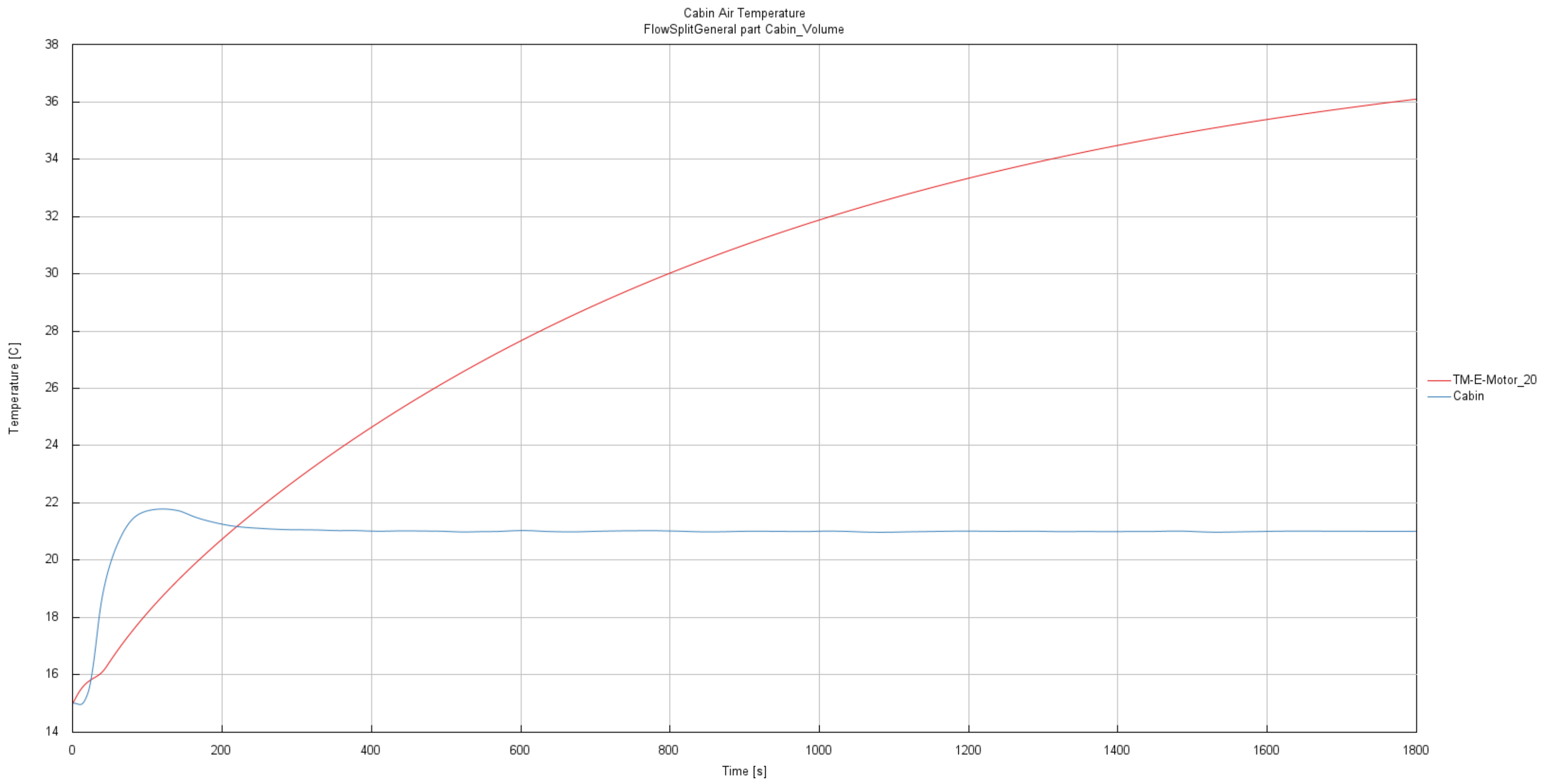


Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-008: Model of advanced HVAC systems for BEV and PHEV

- Cabin and E-Motor temperatures for Winter (-2 degC ambient temperature) heating condition during WLTC cycle. Used layout allow for harvesting heat dissipated from battery and traction e-motor.
- It will be used for the following WPs 009 and **4-WP6-010 Optimization of HVAC system layouts with heat pump for BEV/PHEV based on implementation into vehicle models including trip control**
-

Results – dynamic driving during WLTC; HVAC in heating mode



Fulfillment of goals and deliverables of 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Current State of Deliverables and Fulfillment of Goals

- No due deliverable till 12/2023

- **All deliverables for 11/2024 well prepared with already obtained specific knowledge for the following research**

- **Waiting for re-definition of software type results, which is currently too narrow in TA CR definition, changed after the project proposal had been accepted! TA CR definition differs from the generally valid National Board for R&D&Innovations. Possible remedy: Changing of the type of outcomes to "Proven Technologies", which involves newly developed algorithms.**

Current contribution of 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Assessment of the Contribution of Deliverables

Commercial outcome consists in a support of the innovations at all industrial participants, involved in the subproject WPs, and patents. It will be reflected in final development of products in the year 2025 and the following ones.

The close links are between FACME WPs focused on DASY 3-WP08 and boosting devices 3-WP05 and 3-WP06, together with battery vehicles research 3-WP03.

Current contribution of 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Assessment of the Formal/Administrative Goals of the Work Package

Up to now, finances spent are in accordance with the project plan for research organizations CTU-FME and UC-MFF together with industrial partners Skoda Auto and Brano. No issues with commercialization incomes are envisaged. Deliverables are being prepared for fulfillment in the years 2024 and 2025 according to plan.

Current contribution of 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

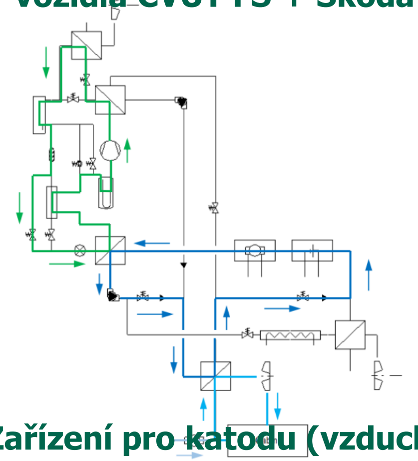
Acknowledgment

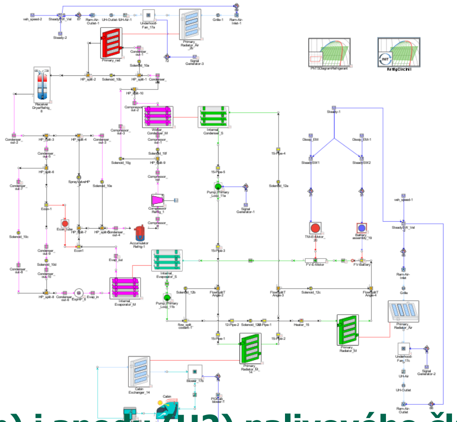
This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Centres II, project # TN02000054 Božek Vehicle Engineering National Center of Competence (BOVENAC).

The fruitful cooperation with all partners, especially MFF CU and Skoda Auto, is highly appreciated.

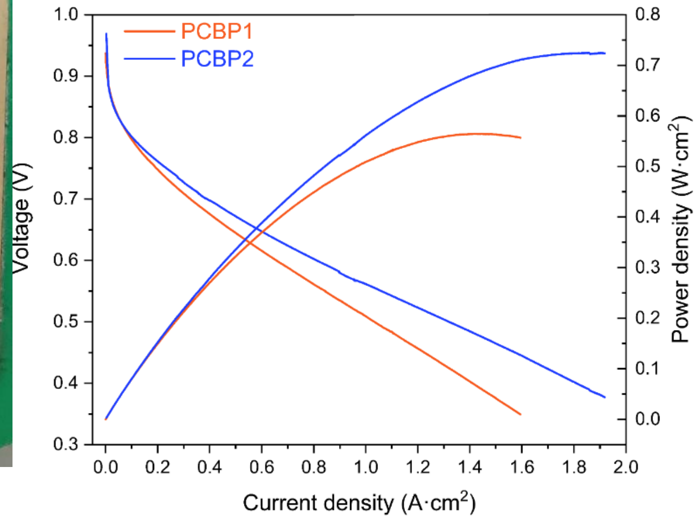
Výsledky 4-WP06 Alternativní hnací jednotky a energeticky náročná příslušenství vozidel: Palivové články a topné/klimatizační systémy v letech 2023-2025

Pokročilé topné a klimatizační systémy pro bateriová a hybridní vozidla ČVUT FS + Škoda Auto

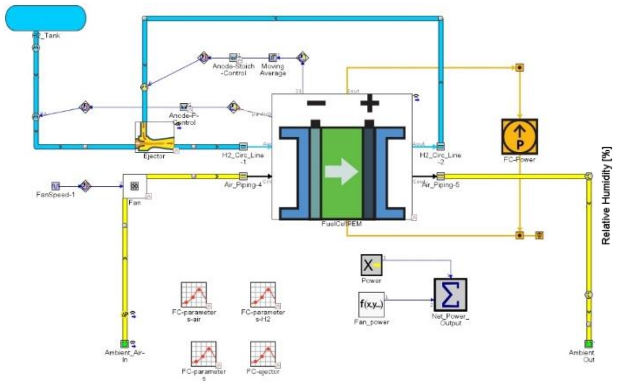


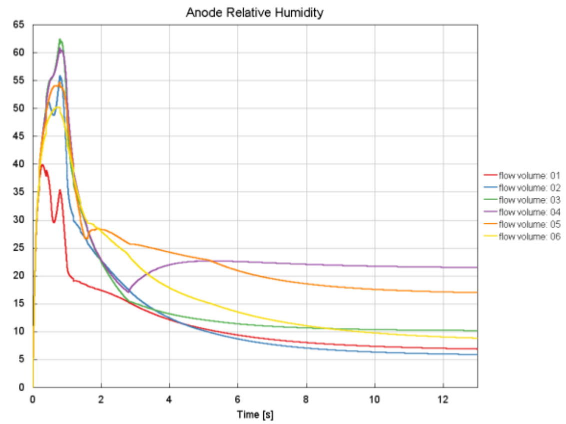


Vliv elektrické vodivosti na vlastnosti palivového článku

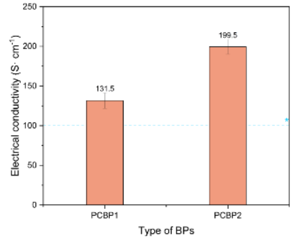


Zařízení pro katodu (vzduch) i anodu (H2) palivového článku s elektricky hnaným kompresorem nebo turbodmychadlem – ČVUT FS





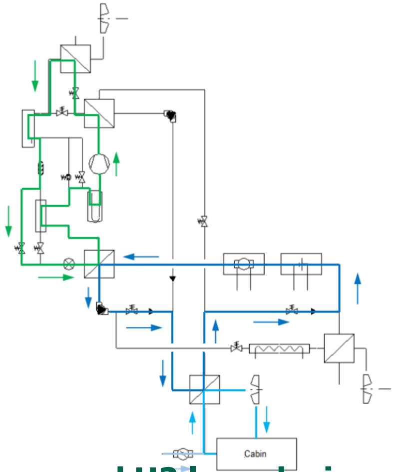
Electrická vodivost

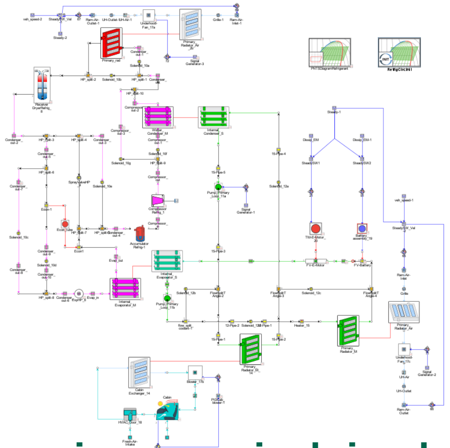


Bipolární desky z epoxidového polymeru s grafitovými nanočásticemi– MFF UK, I. Matolínová

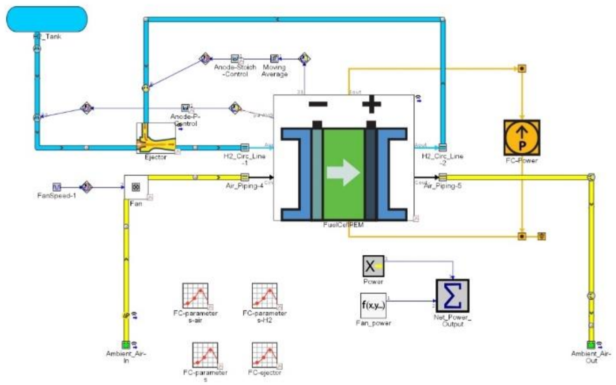
Results of 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management–Achieved 2023-2025

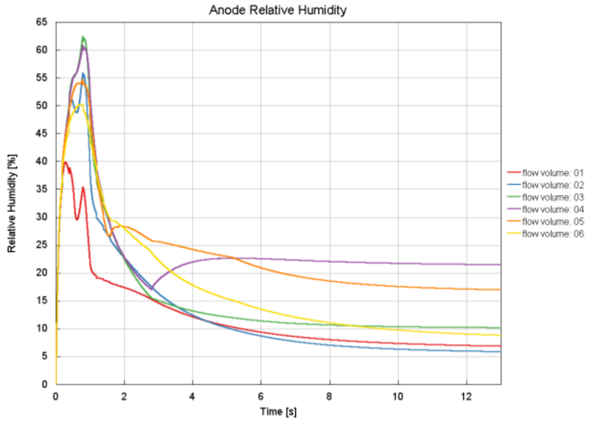
Advanced HVAC systems for BEV and PHEV – CTU FME + Skoda Auto



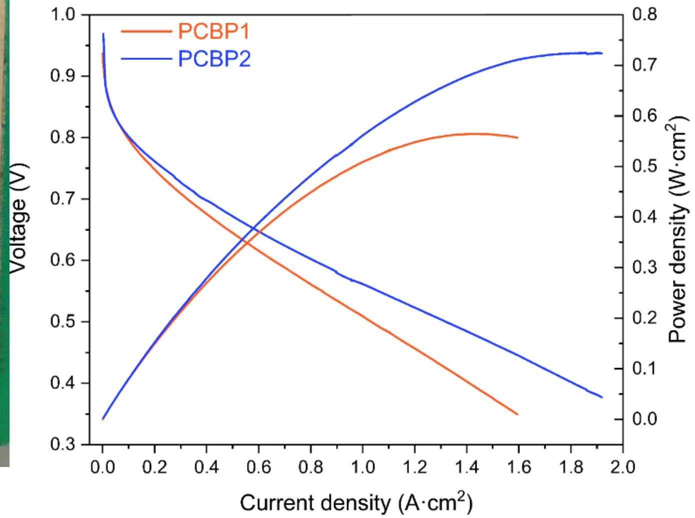


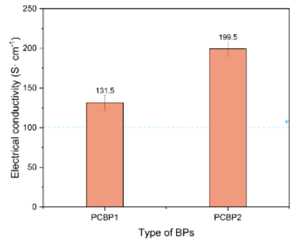
Air-loop and H2 loop devices for using pressurized air exhaust at PEM FCs with electrically supported compressors or TCs – CTU FME





Electrical conductivity effect on PEM fuel cell performance

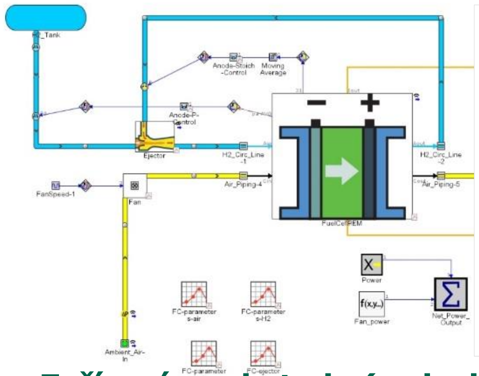


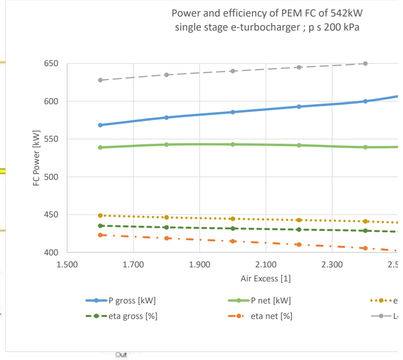


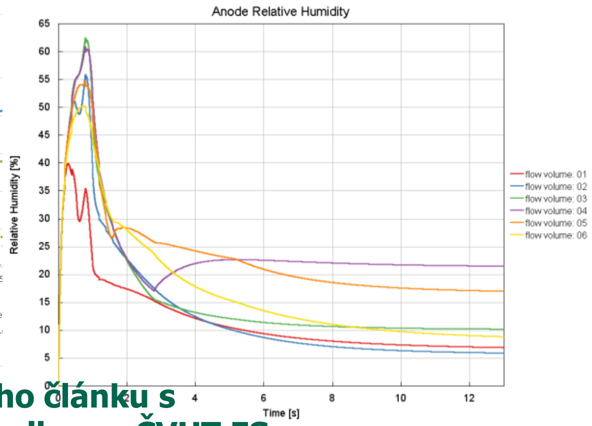
Electrical conductivity

Polymer-composite Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite – MFF CU, I. Matolinova

Výsledky 4-WP06 Alternativní hnací jednotky a energeticky náročná příslušenství vozidel: Palivové články a topné/klimatizační systémy za rok 2023







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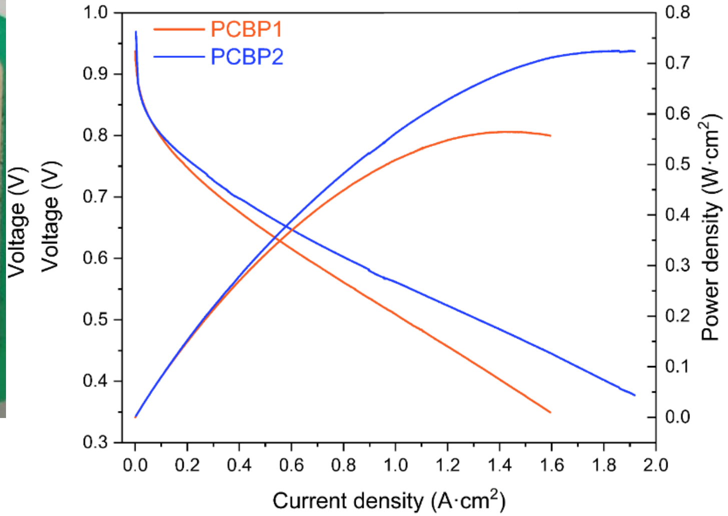
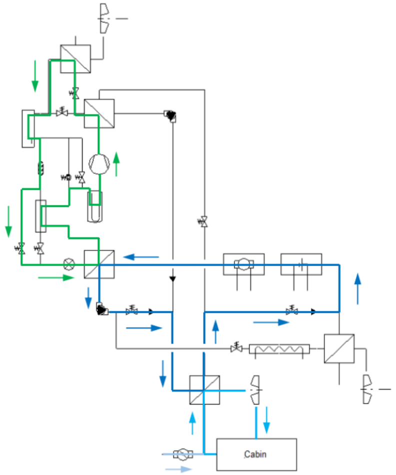
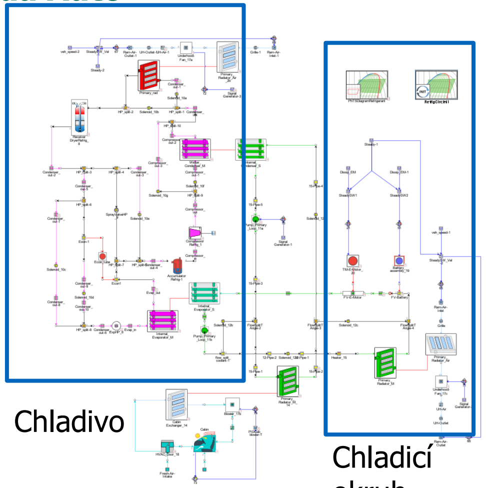
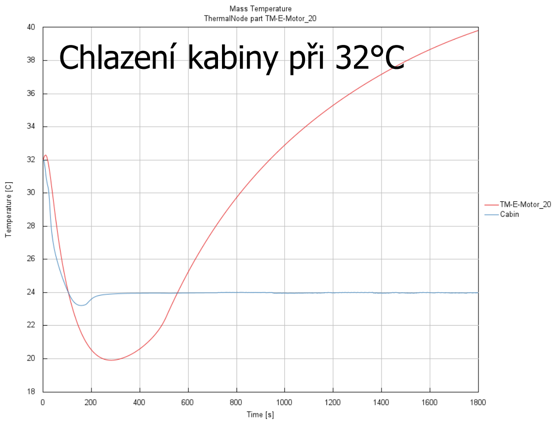


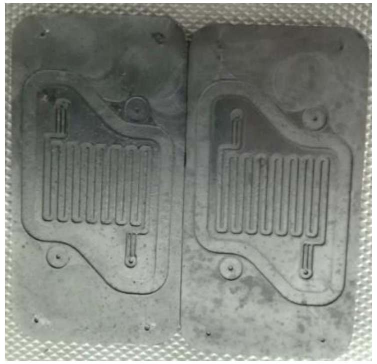




Chladivo

Chladicí okruh





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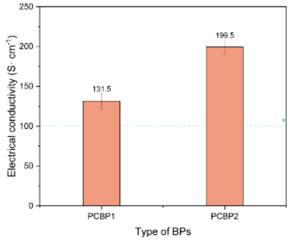

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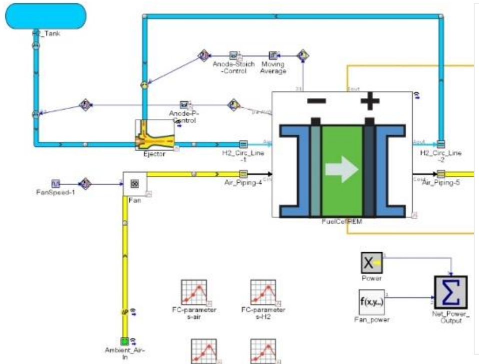

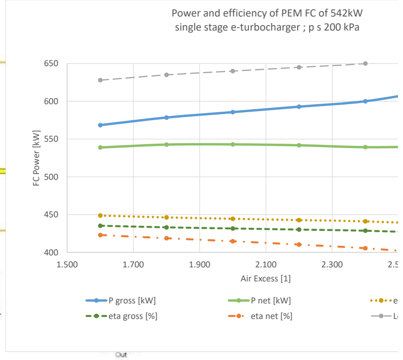

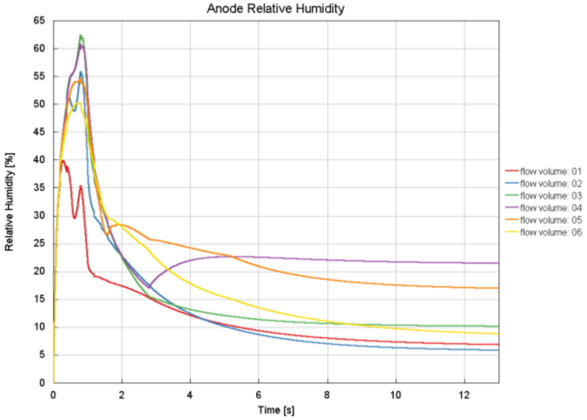

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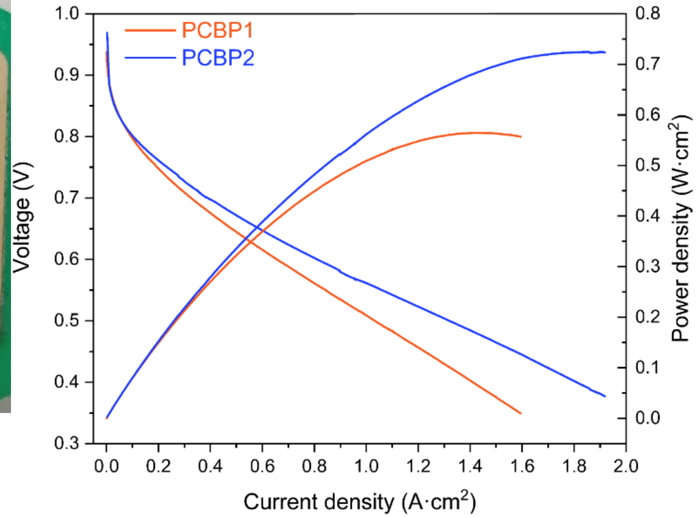

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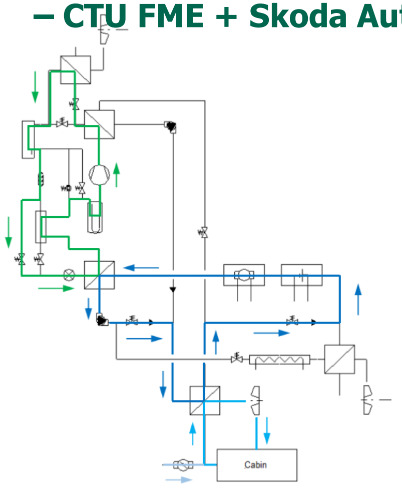
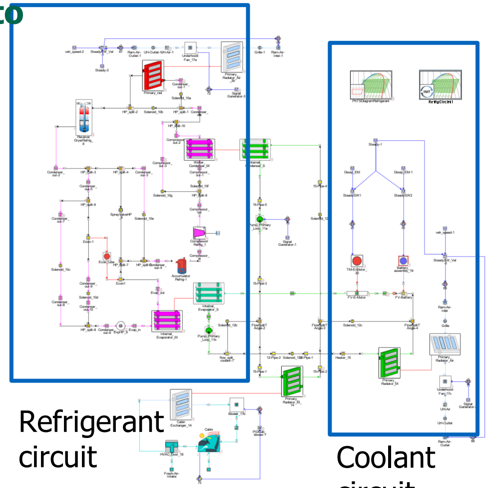
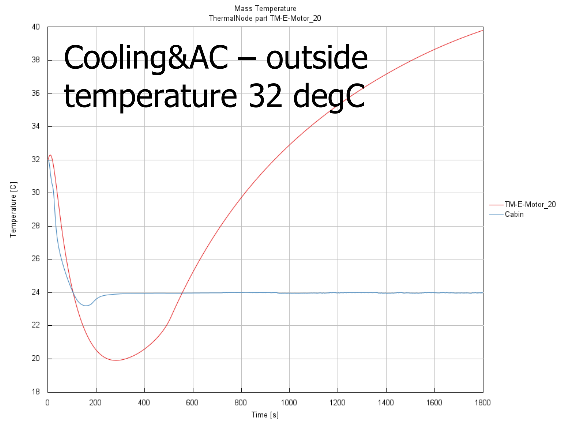
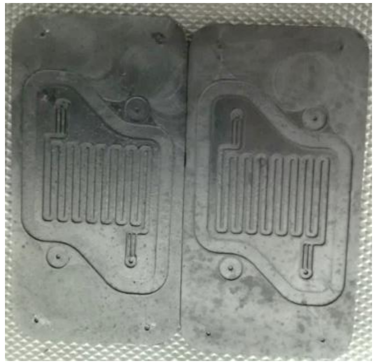




Refrigerant circuit

Coolant circuit





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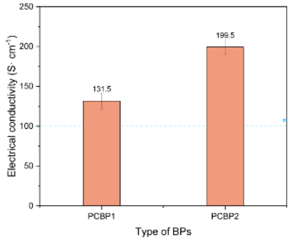

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