Project TE01020054 "Bozek Vehicle Engineering - National Competence Center "

Presentation of Activities and Results Achieved in the year 2024

Subproject: FEFEFOV

Workpackage: 4 – WP06
Fuel Cells and Energy Management for Future Vehicles

Bozek 2024/Mobility Sympo 19. 11. 2024

WP Coordinator: prof. Ing. Jan Macek, DrSc.

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 (PEMFC) design and implementation in vehicles for long range using renewable fuels, suitable for ICEs at emerging markets, and hybrid drives. Moreover, Heating, Ventilation and Air Conditioning (HVAC) systems are optimized for low outlet cooling liquid temperature.

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 (1 Gfunk, 2 Fuzit, 4 R-software) :

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

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 FMP+CTU FME

4-WP06-011: Equipment for electrochemical measurement of gas permeability Fuzit-Registered model (Užitný vzor) CU FMP

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+CU FMP

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
004-5	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
005-6	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
007	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
008-9	4-WP06-008 and 009 Possible HVAC system layouts with heat pump for BEV/PHEV	Jan Macek, CTU FME	YES	YES	No	No
010	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

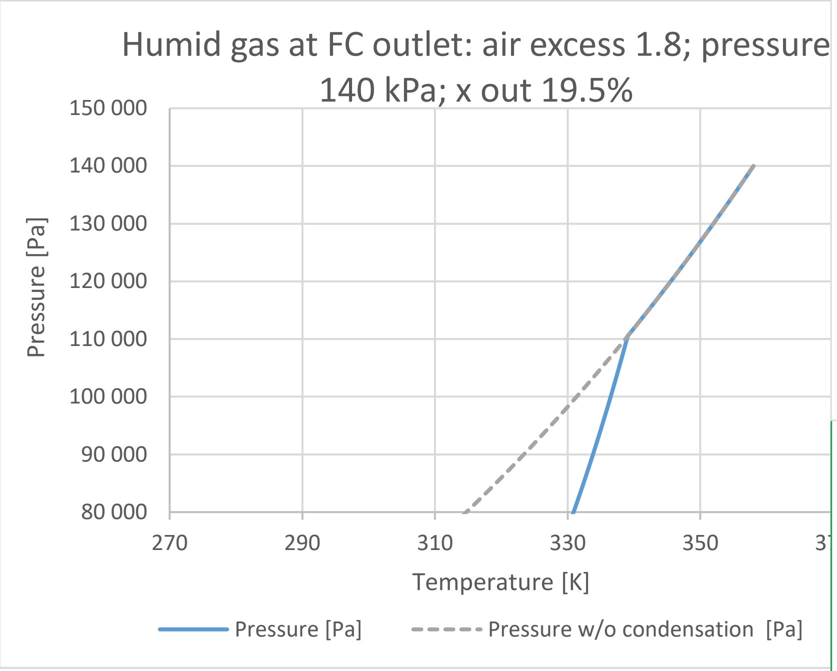
4-WP06-001: Simulation of highly humid air expansion

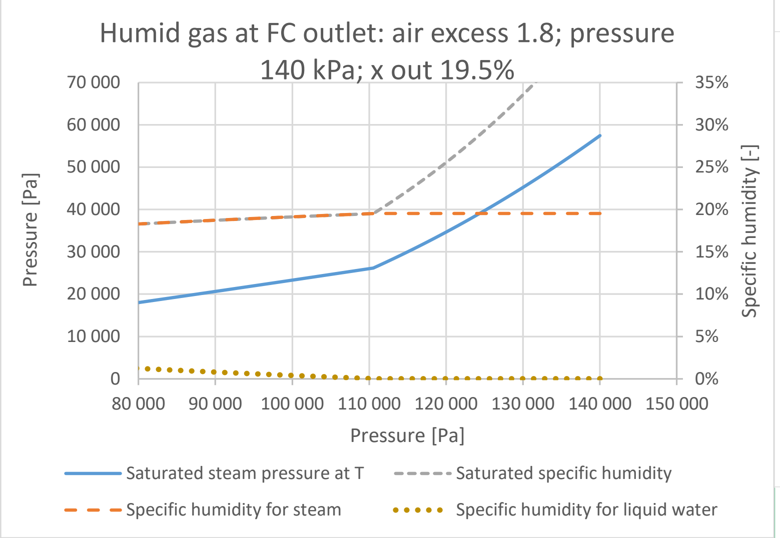
Algorithm and de-bugging - final code in MS Excel and harmonized with GT Suite possibilities:

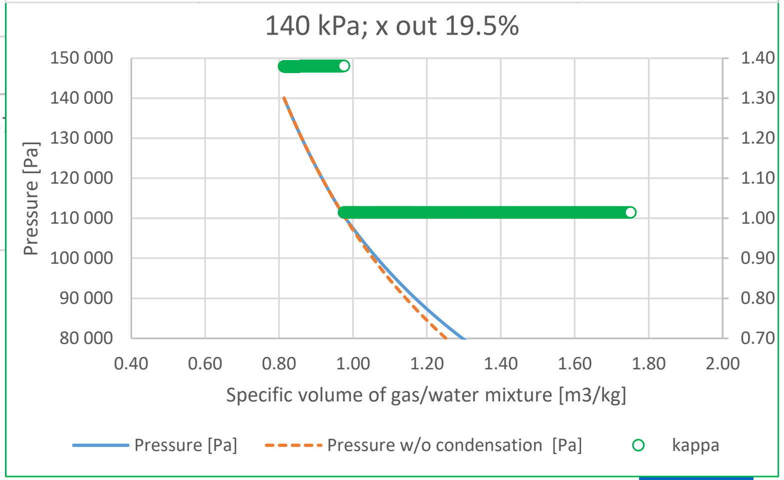
- pressure-temperature dependence with water condensation according to local partial pressure of saturated steam
- involvement of irreversible increase of entropy inside a turbine due to total-to-total turbine efficiency (w/o exit loss)

Turbine total-to-static efficiency was corrected to outlet velocity change due to condensation of water – density increase of humid air mixture.

New tabulated data approach, collecting the pre-calculated results of differential equation integration expansion of humid gas and interpolation in data by regression model has been developed.





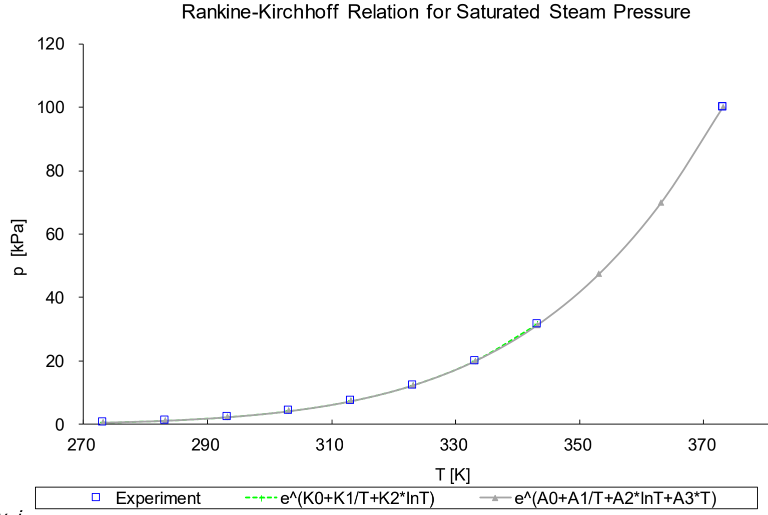


Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

- Differential equation associating pressure – temperature changes with derivatives of enthalpy and specific humidity and turbine irreversible adiabatic change

$$\frac{dp}{dT}=\frac{\frac{\partial h}{\partial T}-c_n}{\frac{1}{\rho}-\frac{\partial h}{\partial p}}=\frac{\frac{\partial h}{\partial T}-\frac{n-\kappa}{n-1}\frac{r}{\kappa-1}}{\frac{1}{\rho}-\frac{\partial h}{\partial p}}$$



- Derivatives are found from

$$\frac{\partial h}{\partial T}=\frac{1}{1+x}\left(\frac{dh_{dry}}{dT}+\frac{\partial x_S}{\partial T}\left(h_{H2O,S}-h_{H2O,L}\right)+x_S\left(\frac{dh_S}{dT}-c_{p,H2O,L}\right)+x\,c_{p,H2O,L}\right)=c_p\Big|^T$$

$$\frac{\partial h}{\partial p}=\frac{x_S}{1+x}\frac{\partial\left(h_S-h_L\right)}{\partial p}+\frac{h_S-h_L}{1+x}\frac{\partial x_S}{\partial p}\approx\frac{h_S-h_L}{1+x}\frac{\partial x_S}{\partial p}$$

- E.g., detailed derivatives are

$$\frac{\partial x_{v,S,i}}{\partial T}=\frac{r_{g,dry}}{r_{H2O}}\frac{\frac{dp_{sat,v,i}}{dT}\left(p_v-p_{sat,v,i}\right)+\frac{dp_{sat,v,i}}{dT}p_{sat,v,i}}{\left(p_v-p_{sat,v,i}\right)^2}$$

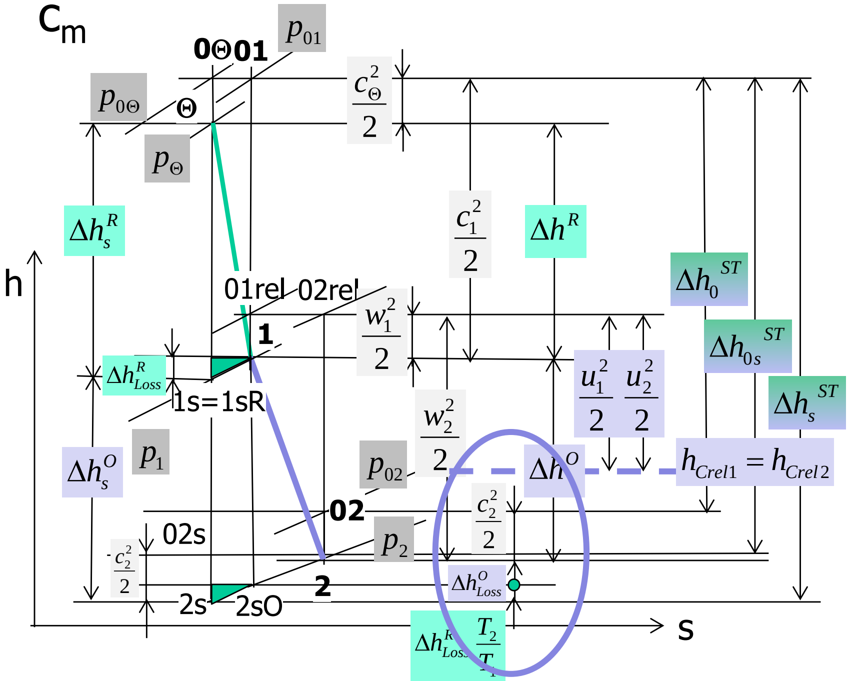
$$\frac{\partial h_{v,i}}{\partial T}=\frac{1}{1+x_v}\left(\frac{dh_{dry,v,i}}{dT}+\frac{dx_{v,S,i}}{dT}\left(h_{H2O,S,v,i}-h_{H2O,L,i}\right)+x_{v,S,i}\left(\frac{dh_{H2O,S,v,i}}{dT}-c_{p,H2O}\right)+x_v c_{p,H2O}\right)=c_p\Big|^T$$

$$\frac{\partial x_{v,S,i}}{\partial p}=-\frac{r_{g,dry}}{r_{H2O}}\frac{p_{sat,v,i}}{\left(p_v-p_{sat,v,i}\right)^2}\quad;\quad\frac{\partial h_{v,i}}{\partial p}=\frac{\frac{\partial x_{v,S,i}}{\partial p}\left(h_{H2O,S,v,i}-h_{H2O,L,v,i}\right)}{1+x_v}$$

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

- stage efficiency (at mean diameter) –total-static - depends on $\mathbf{c_2}$
- polytropic exponent may be used for finding irreversible "heat" from entropy change using c_m



$$\eta_s^{ST} = \frac{h_{0\Theta} - h_{02}}{h_{0\Theta} - h_{2s}}$$

$$\frac{c_2^2}{2} = \frac{c_a^2 + c_{t2}^2}{2} = \frac{c_a^2 + \left(w_{t2} + u\right)^2}{2} = \frac{1}{2}\left(\left(\frac{\dot{m}}{A_{a2}\rho_2}\right)^2 + \left(\frac{\dot{m}}{A_{a2}\rho_2} tg\,\beta_2 + u\right)^2\right)$$

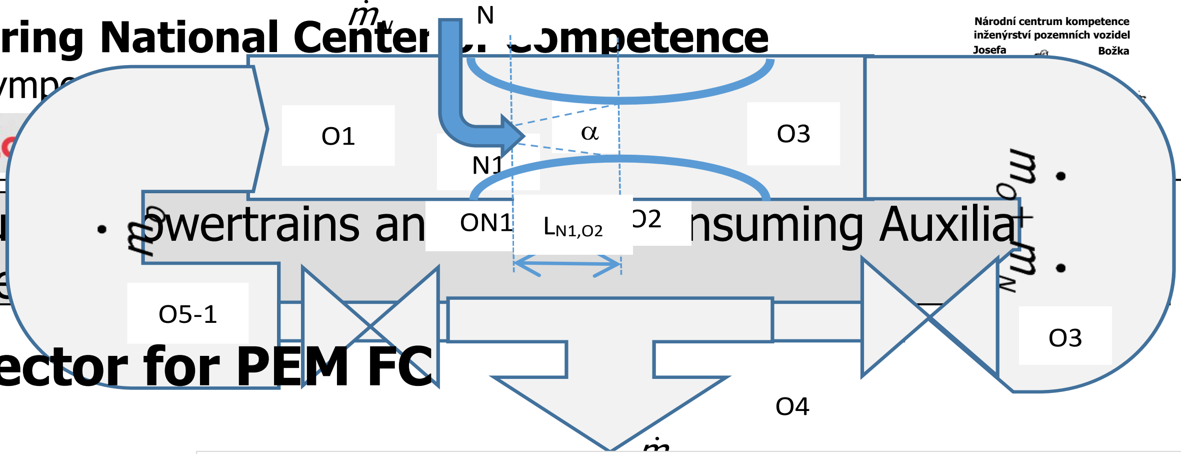
$$\eta_{\mathrm{int},s}^{ST} = 1 - 2\,\frac{\zeta^R \frac{T_2}{T_1}\frac{c_1^2}{2} + \zeta^0 \frac{w_2^2}{2} + \cancel{\frac{c_2^2}{2} = 0}}{c_s^2}$$

$$\frac{n-1}{n} = \frac{\ln\left(1 - \eta_{\mathrm{int},s}^{ST}\left[1 - \left(\frac{p_2}{p_{0\Theta}}\right)^{\frac{\kappa-1}{\kappa}}\right]\right)}{\ln\left(\frac{p_2}{p_{0\Theta}}\right)}$$

$$c_n = \frac{n-\kappa}{n-1}$$

$$TdS = T\left(dS_{rev} + dS_{irr,dis}\right) = dH - Vdp$$

$$\left(dS_{rev} \overset{!}{=} 0\right) + c_{n,irr,dis}\,dT = TdS$$



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

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

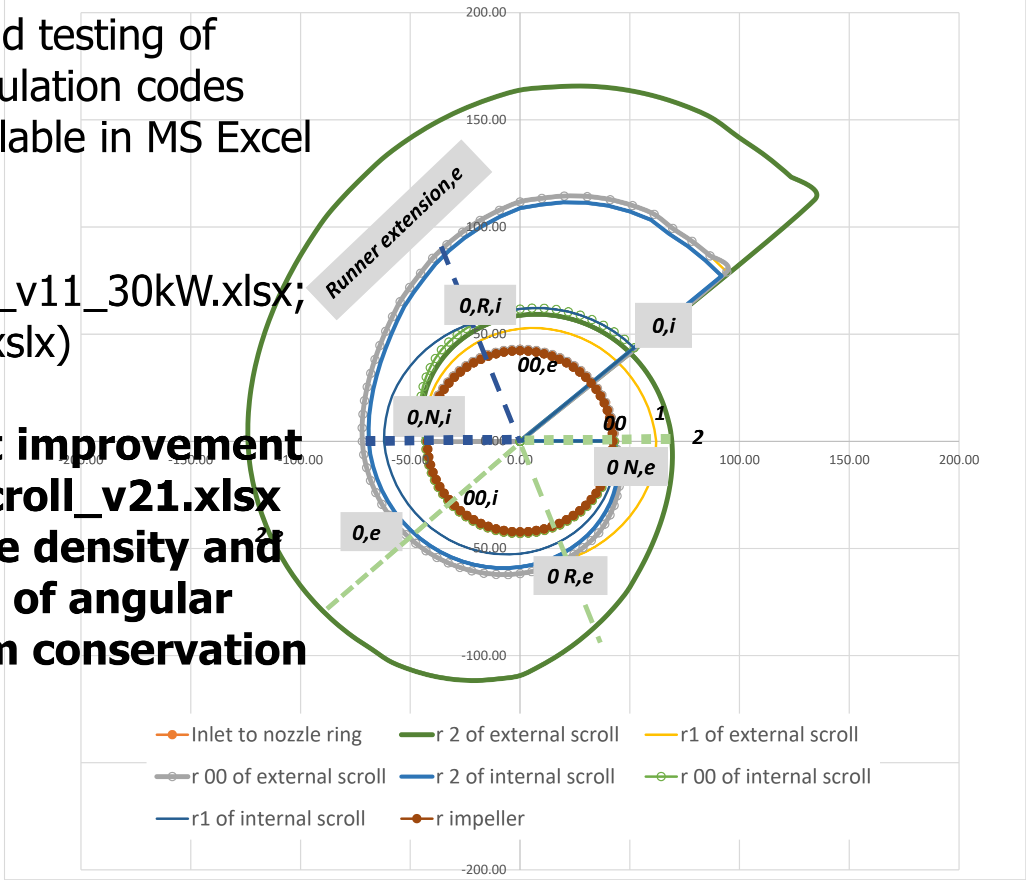
Lay-out of Ejector Circuit

- 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)

Significant improvement of Inlet_scroll_v21.xlsx for variable density and new zones of angular momentum conservation



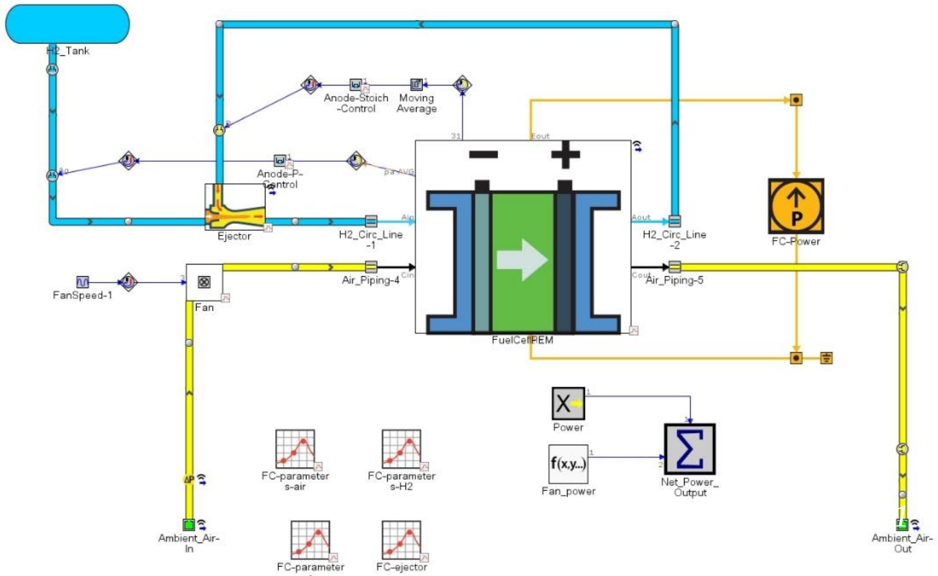
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

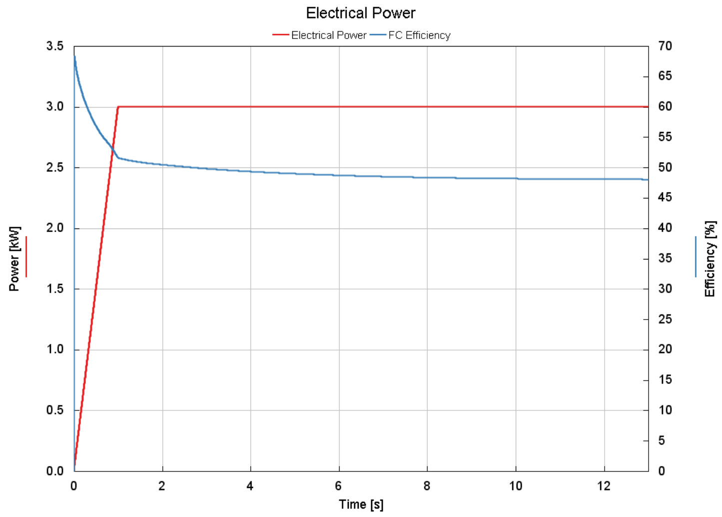
- Analysis of possible principles including COMPREX/HYPREX – already published in USA 2004 (it cannot be patented), but potential possibilities of electrically driven pressure exchanger with cheap steel or aluminum rotor (low temperature of gases) and suitable humid gas recirculation
- Selection of simulation codes already available in MS Excel
- TURBO-v13_PEMFC_v11_30kW.xlsx;
- Ejector_v6.xslx;

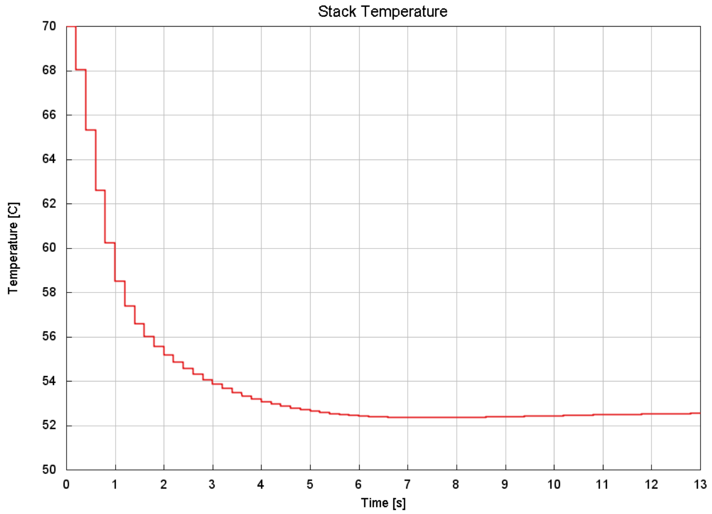
- Warming-up of humid gas with high water contents - cooling effect
- Simulation tool GT Suite using the results of 4-WP001.

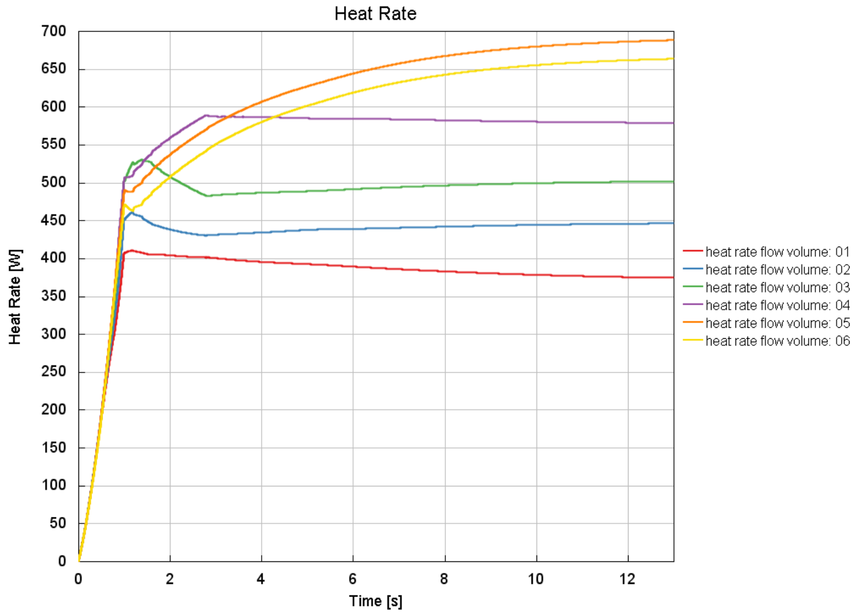


Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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





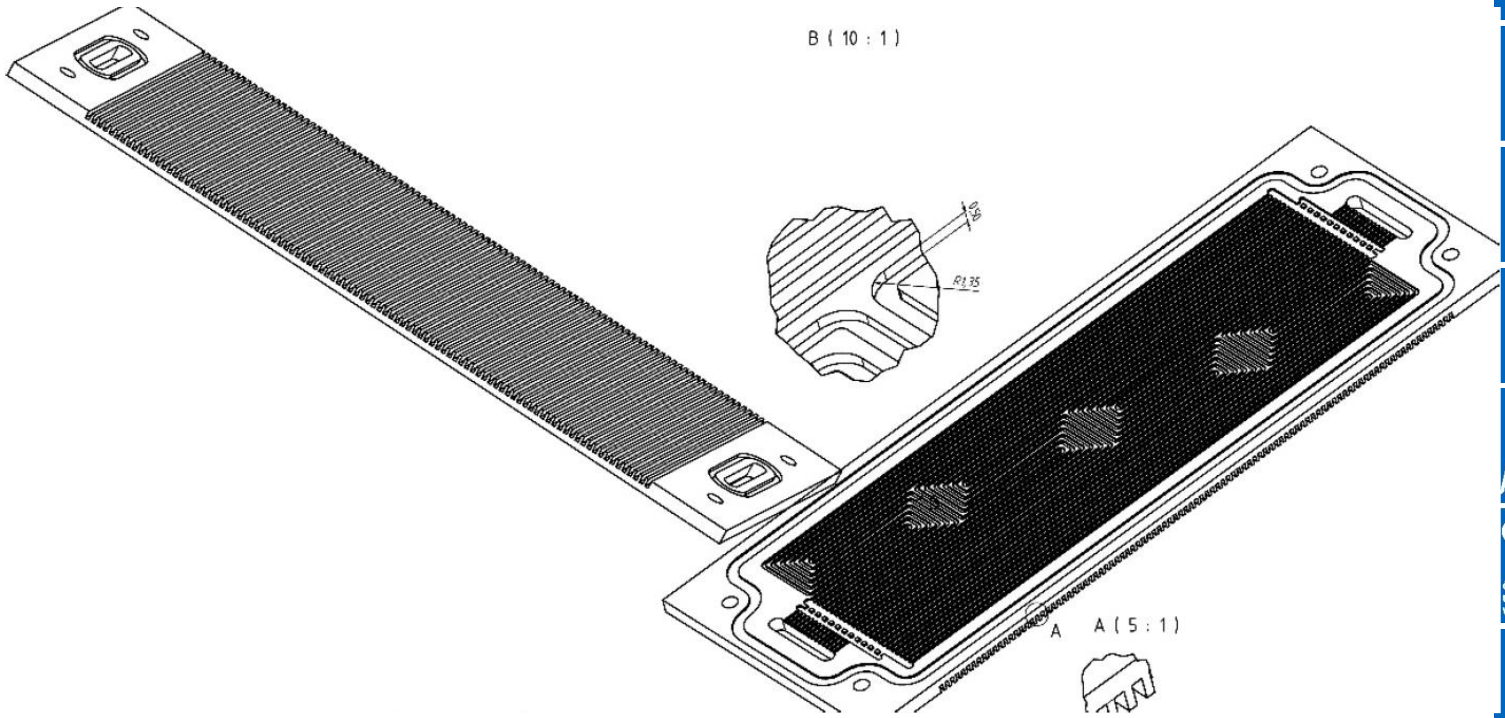


Transient results of PEM FC simulation in GT Suite: Electric power and FC efficiency during operation mode defined by anode stoichiometric ratio 1.3 and cathode stoichiometric ratio 2.1 in GT Suite

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

4-WP06-005 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

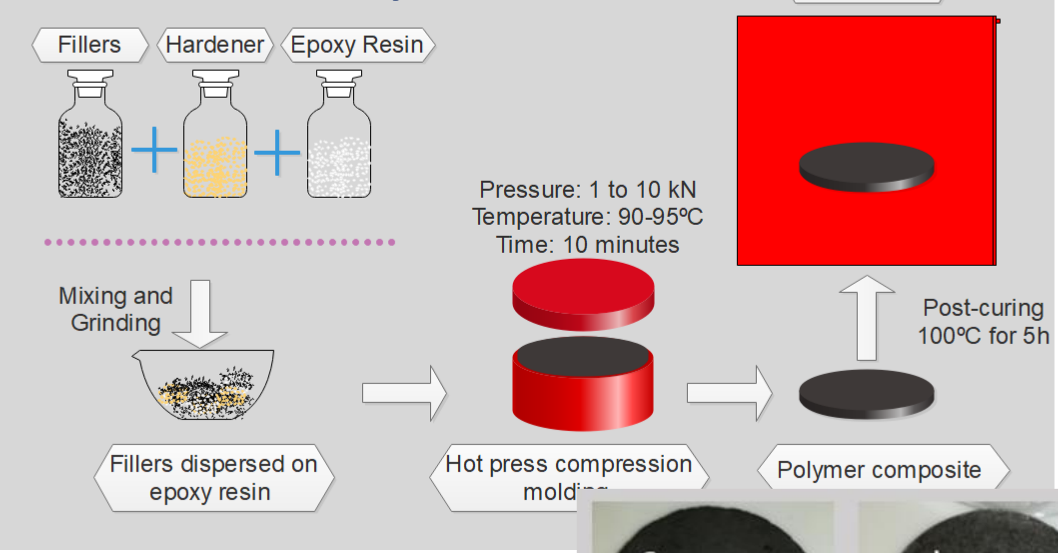
> *If a major project is truly innovative, you cannot possibly know its exact cost and its exact schedule at the beginning. And, if in fact you do know the exact cost and exact schedule, chances are that the technology is obsolete*
>
> Joseph G. Gavin, Jr
>
> Director, Lunar Landing Module, Apollo Programme – Grumman Aircraft Engineering Corp

Research Risks - © Neville Jackson, Ricardo, Eucar Conference 2012

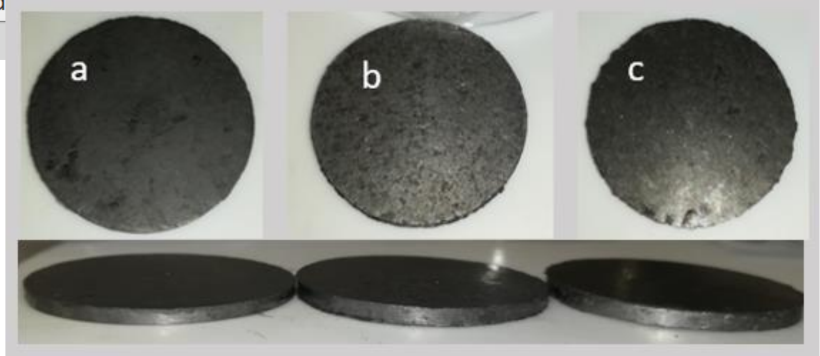
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite



Experimental 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

Technical problems

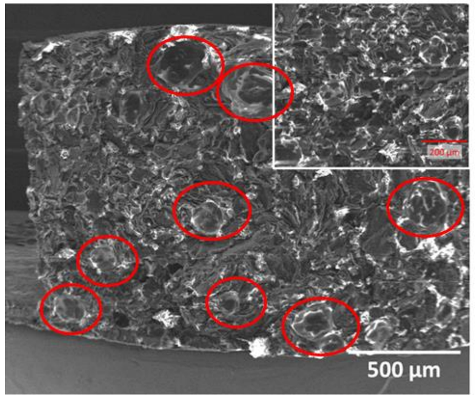
- 1) Homogeneity
- 2) Curing conditions
- 3) Demolding
- 4) Post curing conditions

Technical problems for the fabrication of polymer composite bipolar plates

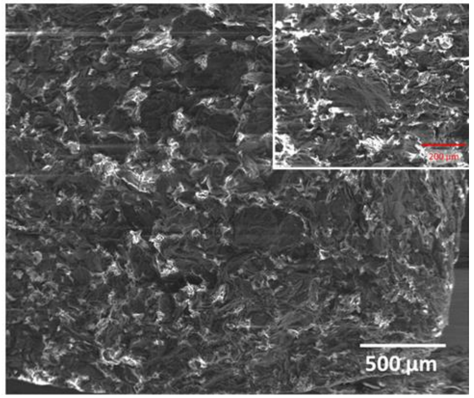
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

TEG 6 wt.% dry method

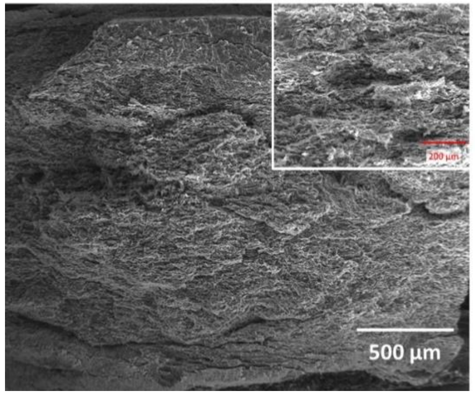


TEG 6 wt.% wet method

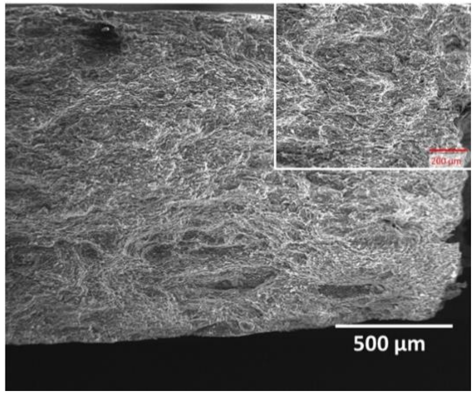


SEM cross-section pictures

SG 60 wt.% dry method

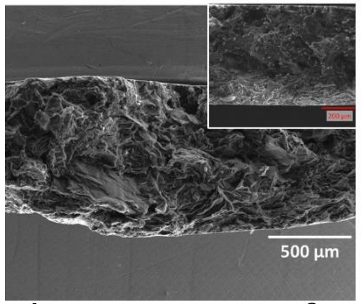


SG 60 wt.% wet method

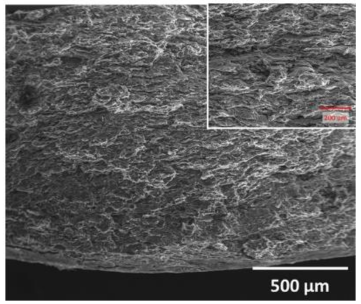


1) Homogeneity

TEG 20 wt.% dry method



TEG 20 wt.% wet method



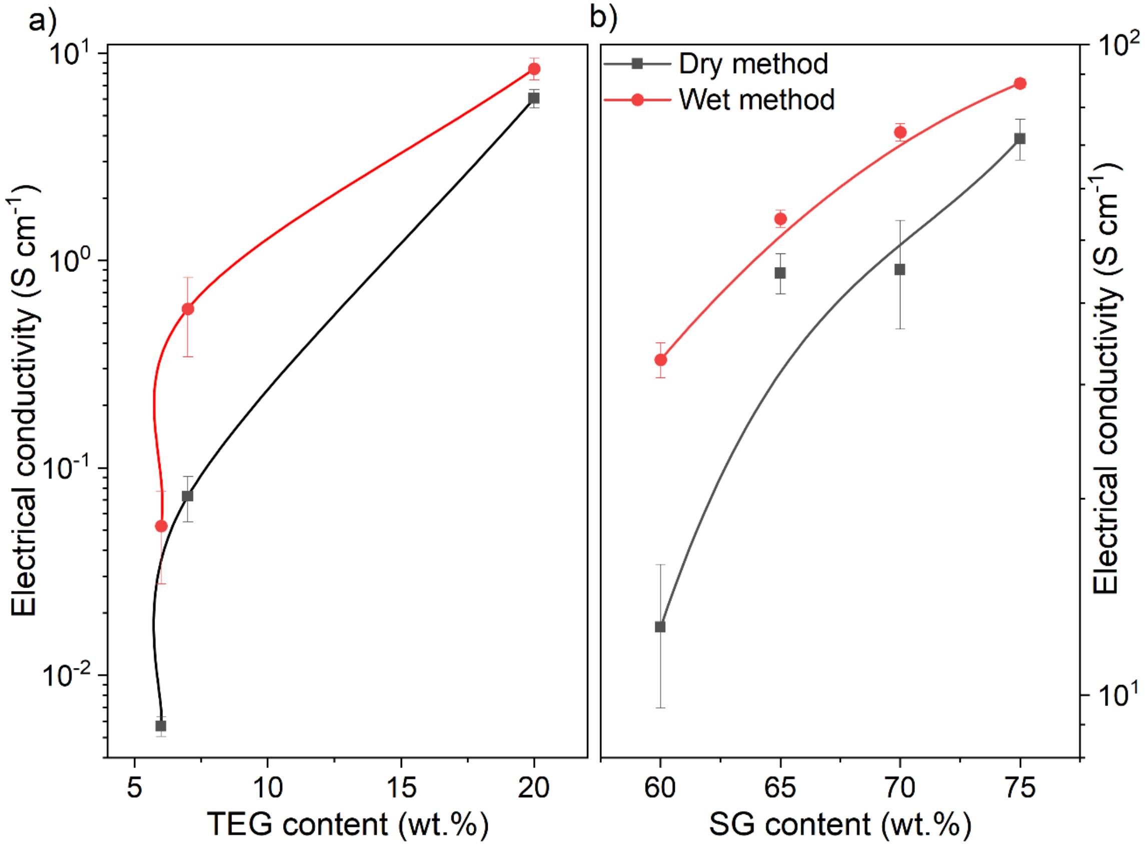
Differences between dry and wet mixing of components:

- *Composites prepared using dry methods tend to demonstrate more defects throughout the bulk material and exhibit chunks of unmixed epoxy, compared to those prepared using wet techniques.*
- *The usage of acetone improves the dissolution of the epoxy resin prepolymer and hardener, facilitating a uniform coating of the filler surface with a fine layer of prepolymer. This process not only increases the amount of filler but also improves its distribution within the matrix.*

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

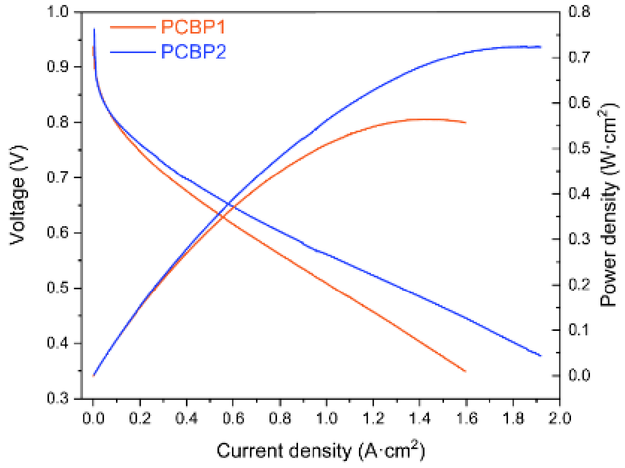
4-WP06-005 and 006 Design and realization of short stack with three 100cm2 fuel cells with opened cathode on the base of carbon material

1) Homogeneity: Differences between dry and wet mixing of components



The electrical conductivity is affected by the type of method, showing one order of magnitude higher values for the polymer composites prepared by the wet technique.

Electrical conductivity effect on PEM fuel cell performance



The wet mixing method enhances the homogeneity and dispersion of the fillers within the epoxy resin. As a consequence, the electrical conductivity values are improved in comparison with the dry mixing method.

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

3) Demolding: release agent vs. teflon paste

- *Base of h*ydrocarbons, C7-C9, isoalkanes
- *Compatible with a*ll standard resins and gel-coats, polyester, vinylester, epoxy etc.
- All standard tool surfaces; epoxy, PU, polyester, vinylester, aluminium, stainless steel, glass, etc.
- Suitable for use in elevated temperature curing processes up to 175°C

EASY-LEASE CHEMICAL RELEASE AGENT

- *High viscosity, good lubrication properties, good electrical resistance properties.*
- *Good resistance against acids, bases and standard*
- *solvents - except fluor components.*
- *Temperature stable from -30 to +290 °C*

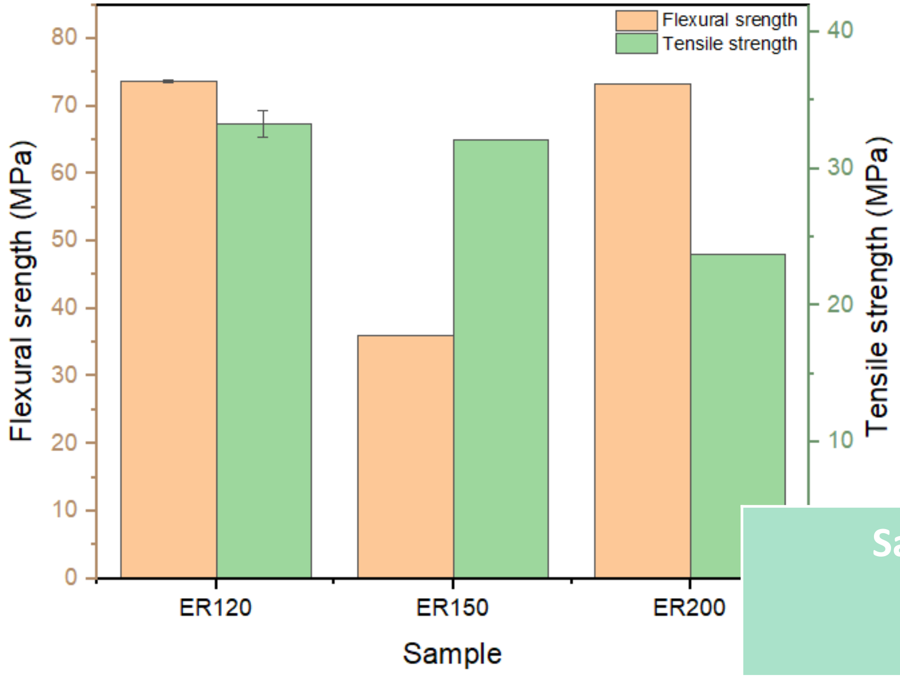
PTFE Paste

The usage of PTFE paste as a separator between mold and polymer composites gives better results in comparison with the release agent. ***The bipolar plate has less defects and a smoother surface.***

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

4) Post curing: mechanical properties



The epoxy resin post-cured at three conditions:

- *the highest flexural and tensile strength observed for epoxy resin post-cured at 120 °C.*
- *while at 150 °C the tensile strength is good enough, the flexural strength is deficient.*
- *a similar effect happens at 200 °C, however, the lower value is for the tensile strength.*

Sample	Description	Flexural strength (Mpa)	Tensile strength (Mpa)
ER120	Post-cured at 120 ºC for 3h	73.7	33.3
ER150	Post-cured at 150 ºC for 3h	36	32.12
ER200	Post-cured at 200 ºC for 3h	73.3	23.74

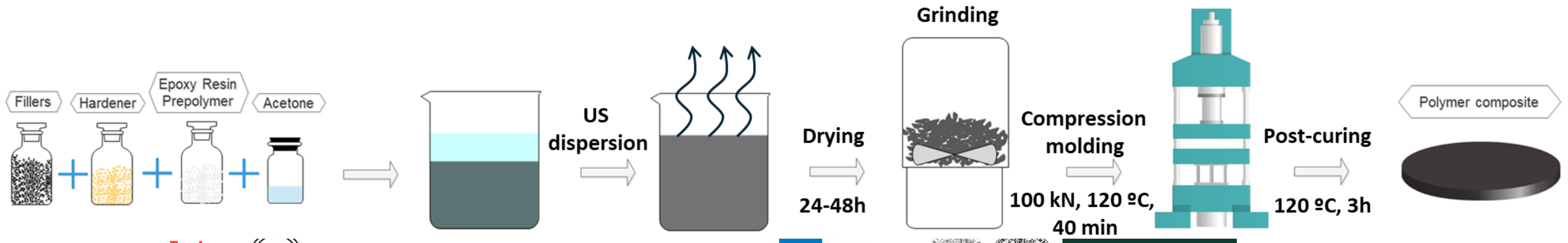
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

Technical problems

- 1) Homogeneity — *Solution* — Wet method
- 2) Curing conditions — *Solution* — 120 °C for 40 min
- 3) Demolding — *Solution* — PTFE paste
- 4) Post curing conditions — *Solution* — 120 °C for 3h

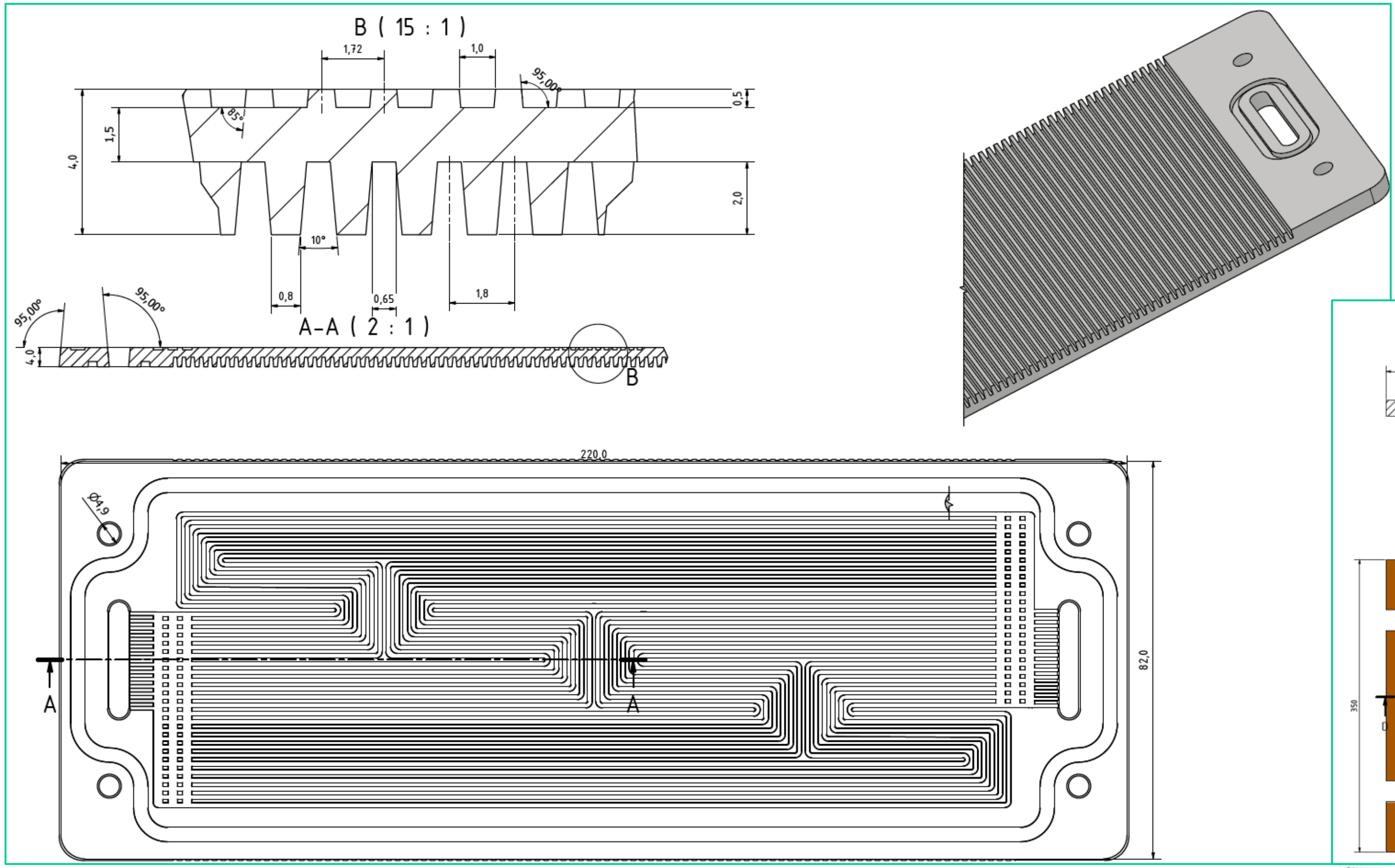
Solutions to the technical problems for the fabrication of polymer composite bipolar plates



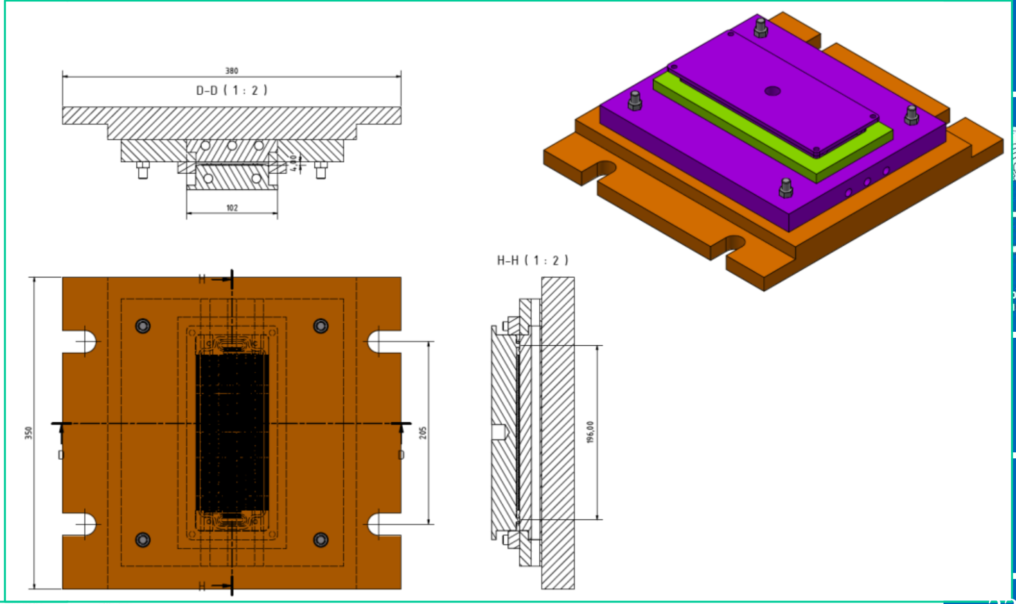
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

Design of bipolar plates with opened cathode



Mold design for pressing bipolar plates

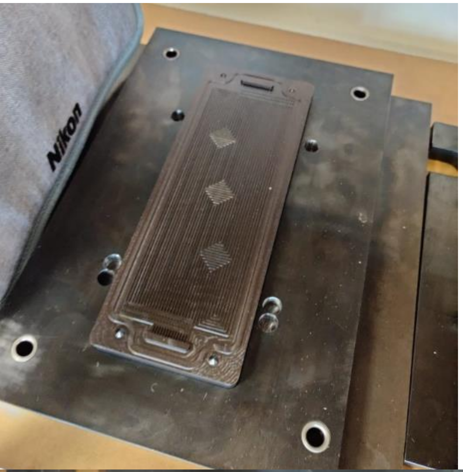


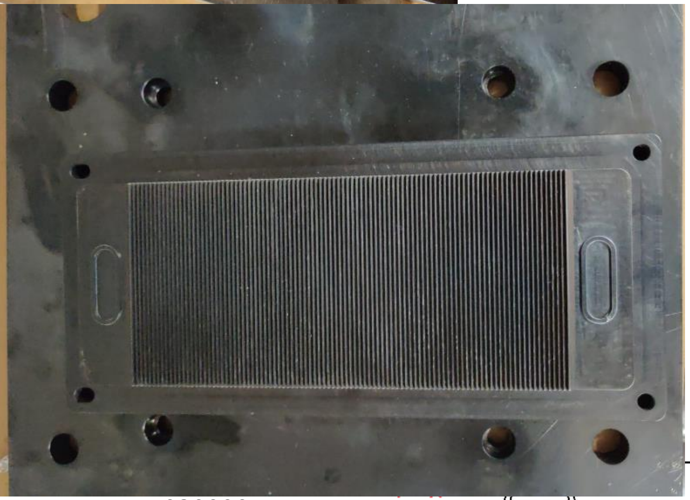
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

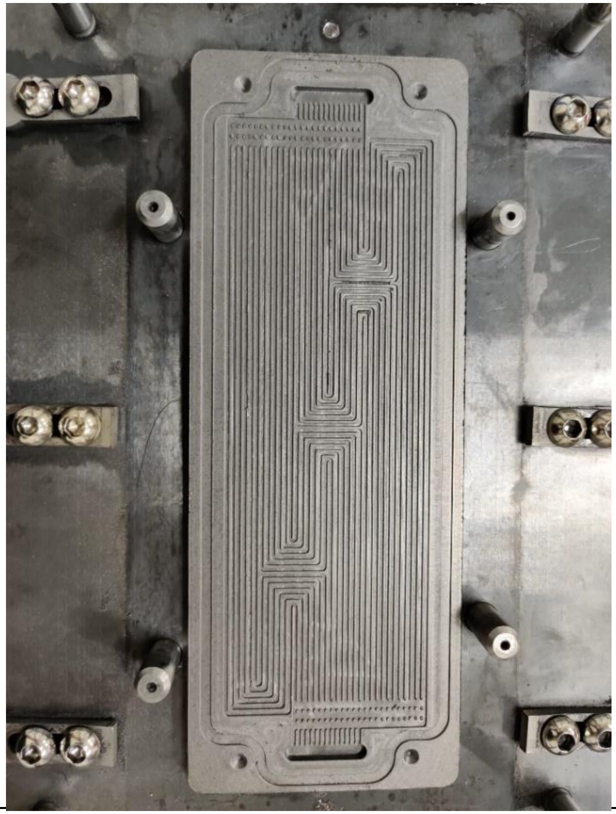
4-WP06-005 and 006 Design and realization of short stack with three 100cm2 fuel cells with opened cathode on the base of carbon material

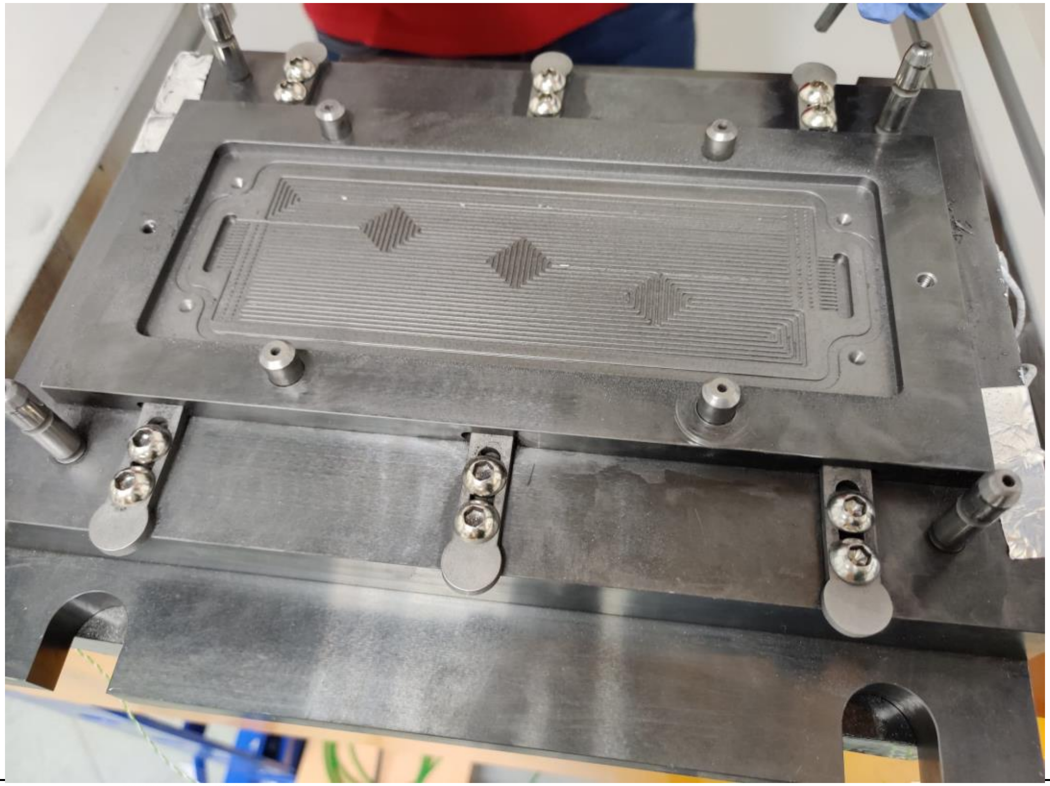
Pressing bipolar plates with opened cathode

150 g of mixture powder: NG 90% + Epoxy 10% (epoxy resin prepolymer + hardener)







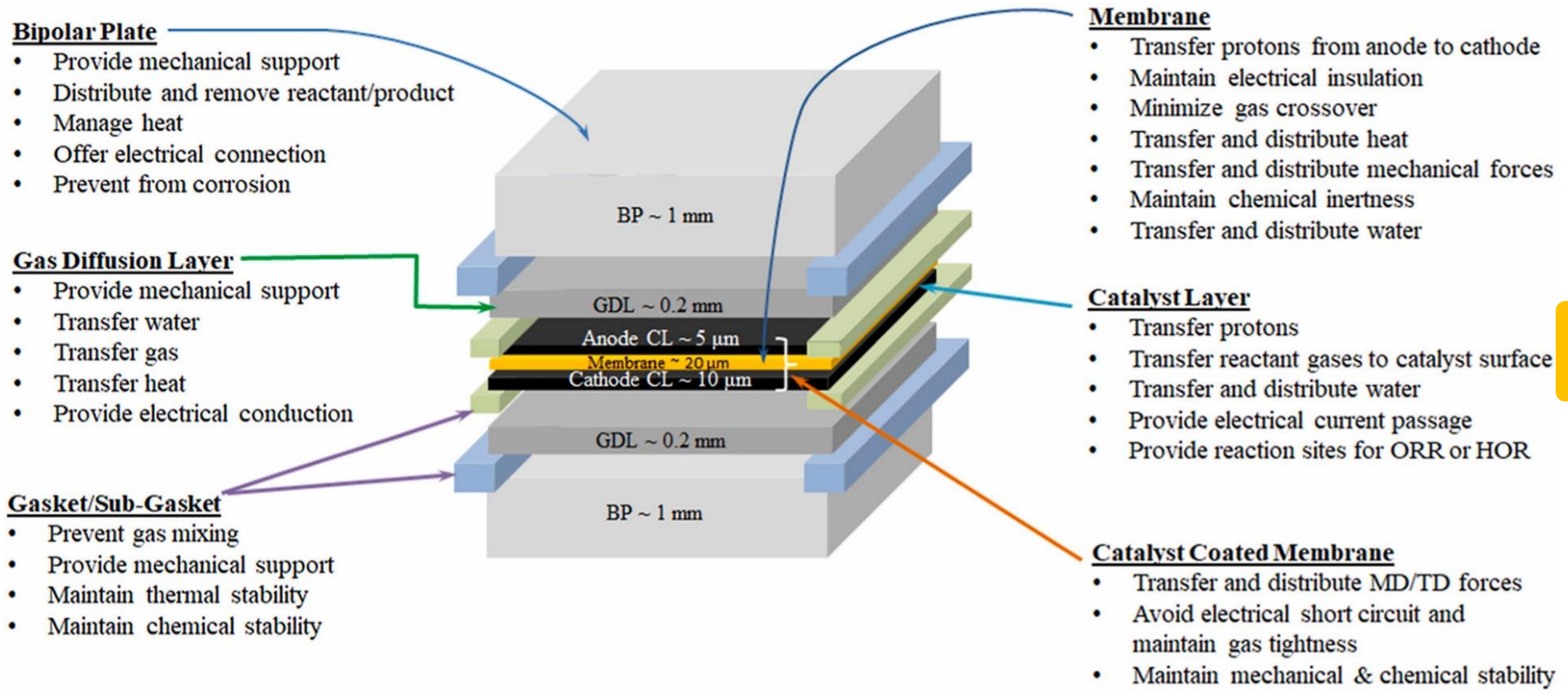


Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

Development of the new electrochemical method for measuring gas permeability of PEM fuel cell components

Gas permeability importance in fuel cells



Current gas permeability methods
- Gas pressure difference
- Flow under pressure difference
- Galvanic and magnetic balance
- Trace gas analysis
- Volumetric analysis
- Electrochemical double cell

Yuan X-Z. et al. J Power Sources (2021) 491

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

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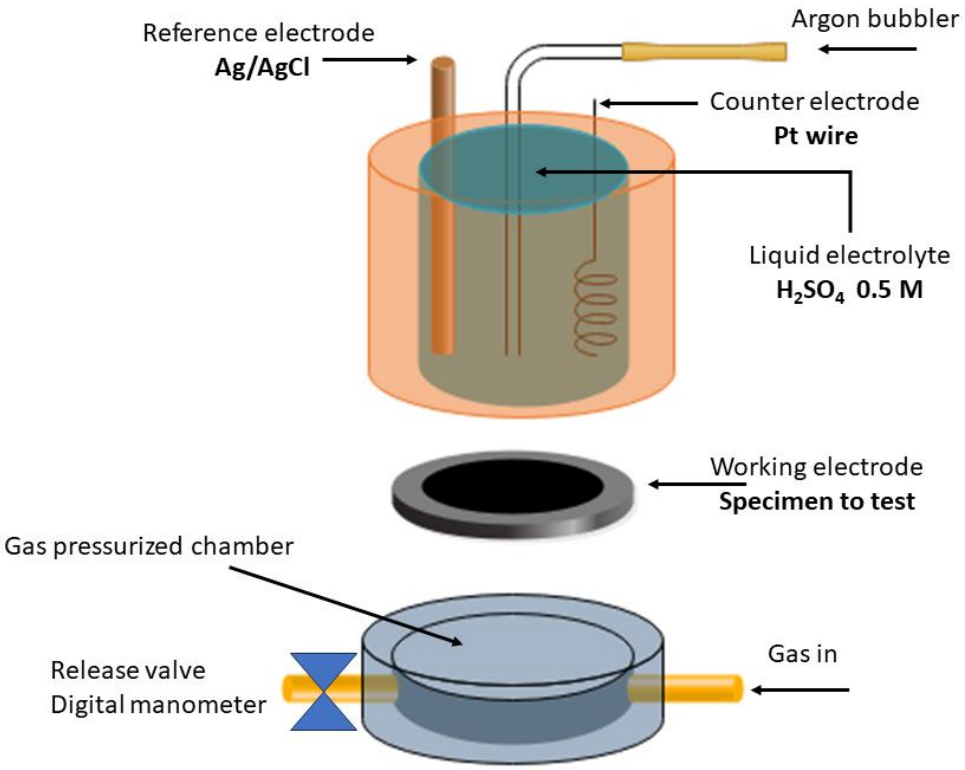


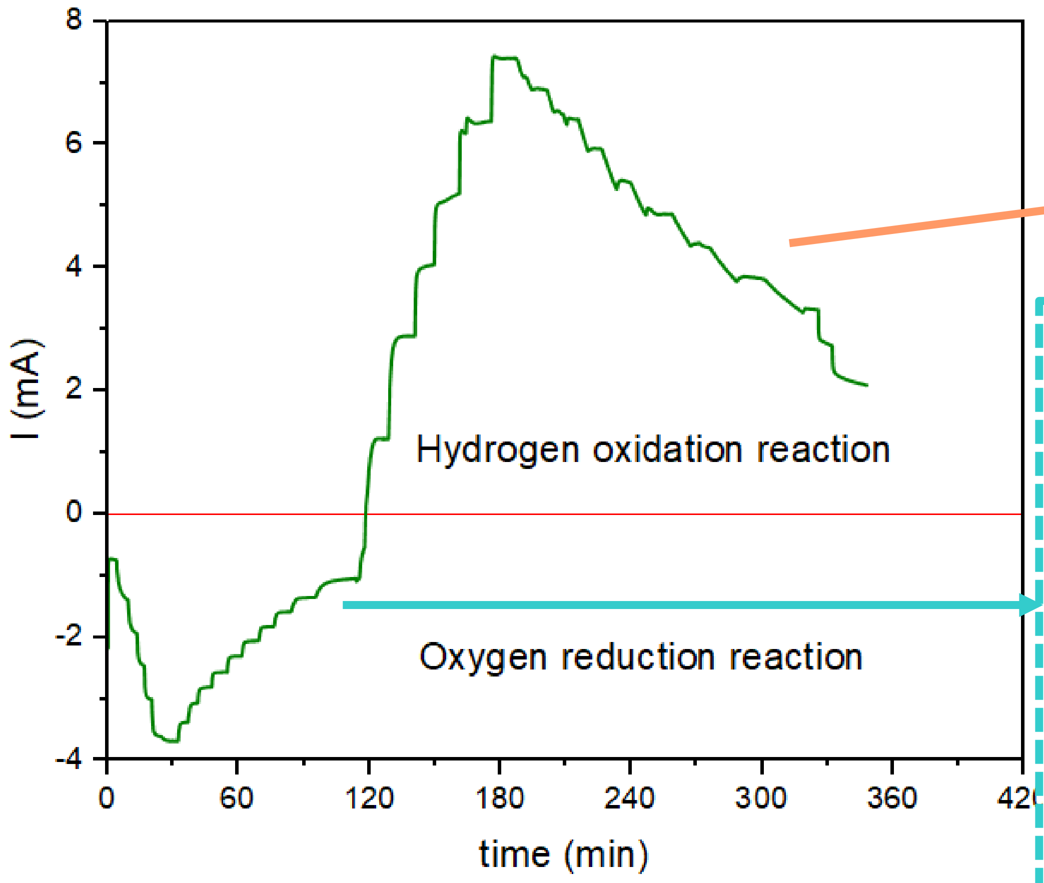
Experimental set-up

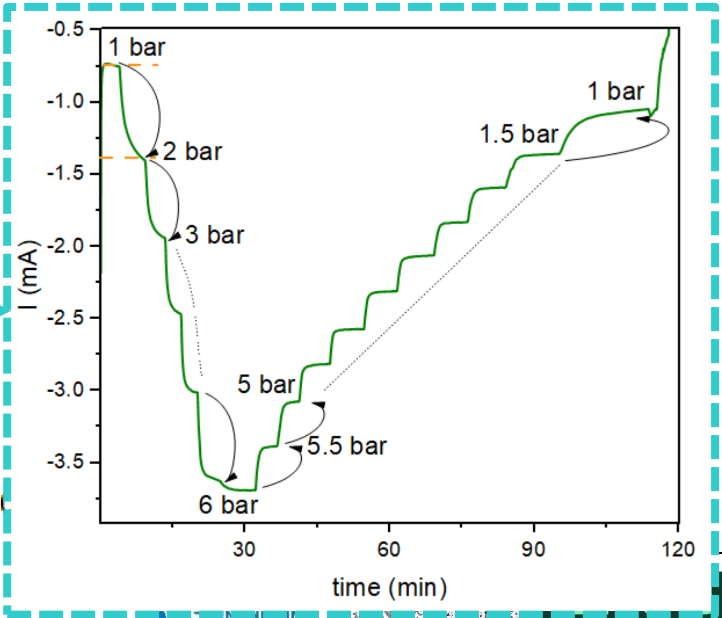
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

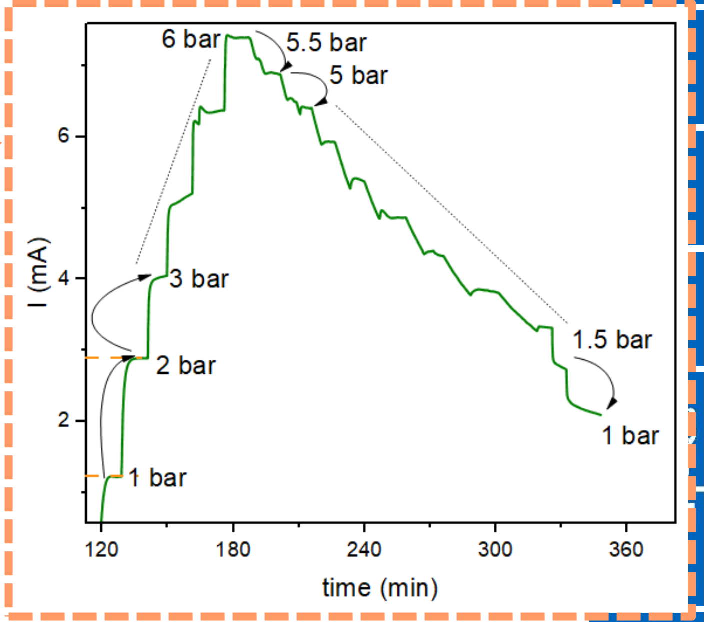
4-WP06-005 and 006 Design and realization of short stack with three 100cm2 fuel cells with opened cathode on the base of carbon material

Development of the new electrochemical method for measuring gas permeability of PEM fuel cell components

Results







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

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Equations and assumptions

Faraday's Law $J = \dfrac{I}{ne^{-} \cdot F}$

Fick's Law $J = \dfrac{D \cdot (C - C_0)}{thickness}$

The coefficient of Diffusivity (D) is obtained

Permeability rate $P = \dfrac{volume\ of\ gas\ at\ STD \cdot thickness}{area \cdot time \cdot pressure\ drop}$

Assumptions:

- *The gradient of concentration goes from the pressurized chamber to the top of the catalyst layer.*
- *The concentration of gas on the catalyst is zero → the catalyst reacts with all the gas molecules.*
- *The pressure drop in our case is the pressure we applied.*

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

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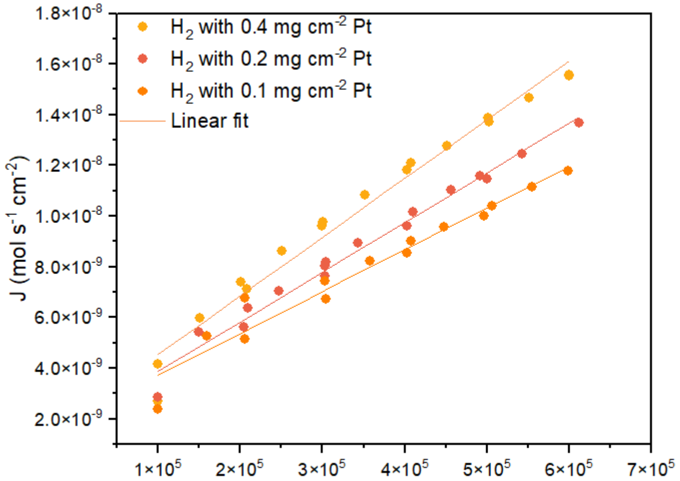
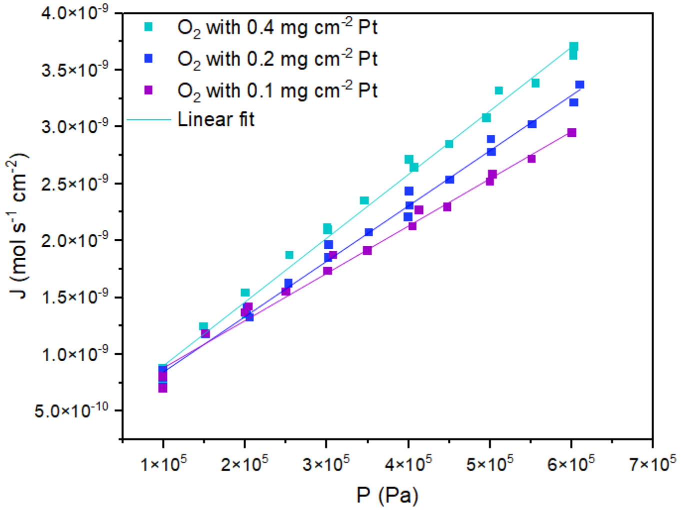
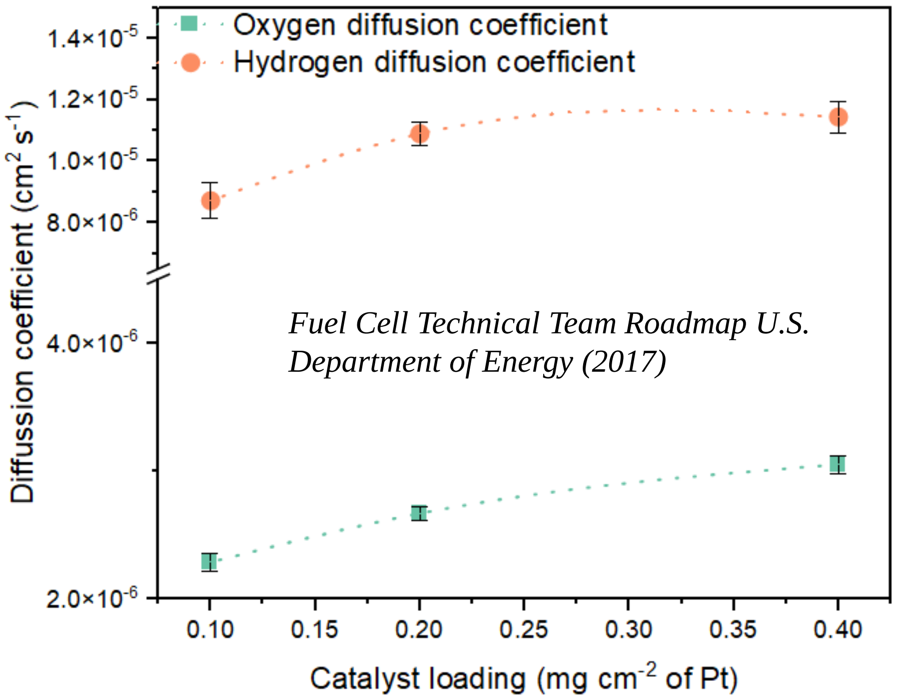




Treated results

Diffusion coefficient at different catalyst loading



Permeability at different catalyst loading

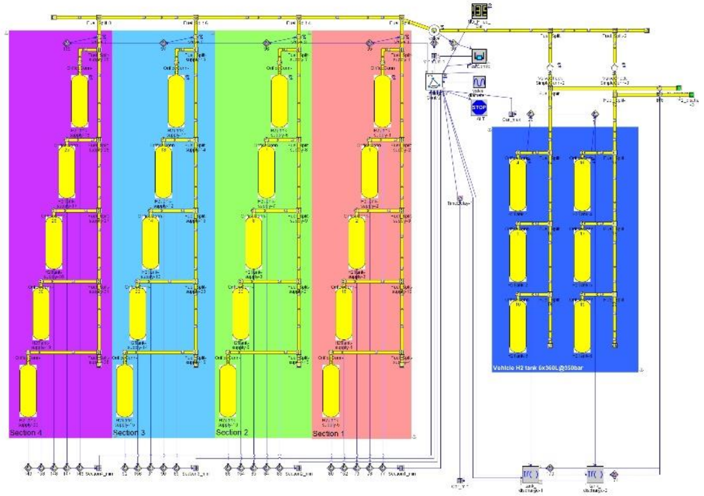
Permeability (Std cm^3 cm s^{-1} cm^{-2} Pa^{-1})	H_2	O_2
0.4 mg cm^{-2} Pt	1.5E-10	3.4E-11
0.2 mg cm^{-2} Pt	1.3E-10	3.1E-11
0.1 mg cm^{-2} Pt	1.2E-10	2.9E-11

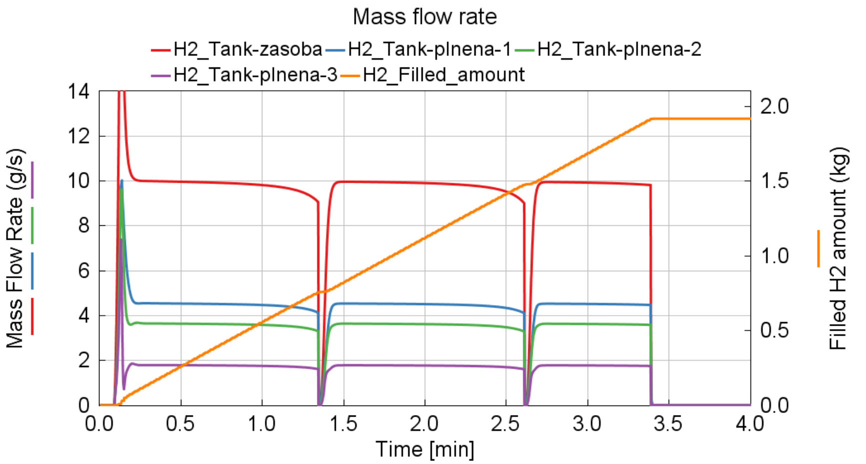
DOE target of the H_2 permeability for bipolar plates
$\rightarrow$
2E-6 cm^3 cm^{-2} s^{-1} Pa^{-1}

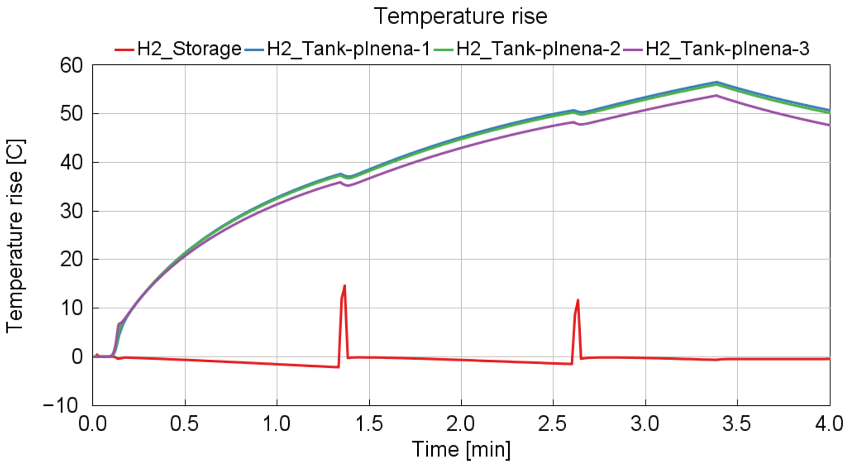
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

- 20 pressurized tanks divided into several sections
- Hydrogen tank volume 360 l
- Initial hydrogen storage pressure 380 bar
- Filling of hydrogen utility track – 6x360 l at 350bar
- Simulation of pressure tanks warm-up during filling





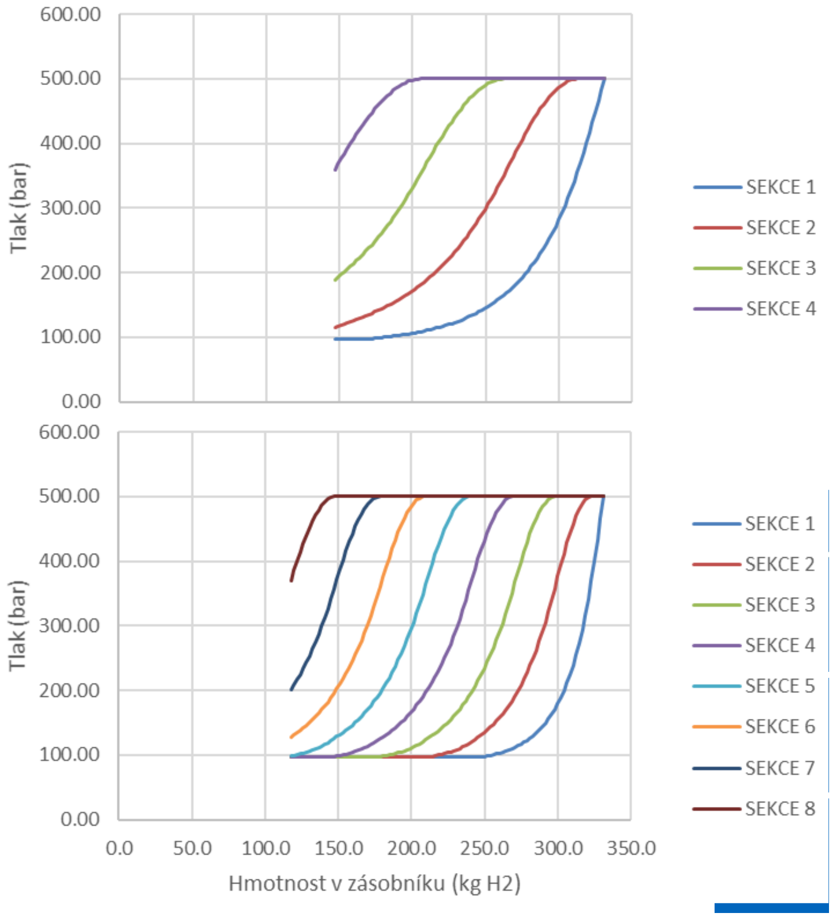


Doleček V., Hatschbach P., MOBILE HYDROGEN FILLING STATIONS. . 55. mezinárodní vědecká konference zaměřená na výzkumné a výukové metody v oblasti vozidel a jejich pohonů, TU v Liberci, 2024, ISBN 978-80-7494-711-7, p. 100-110

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

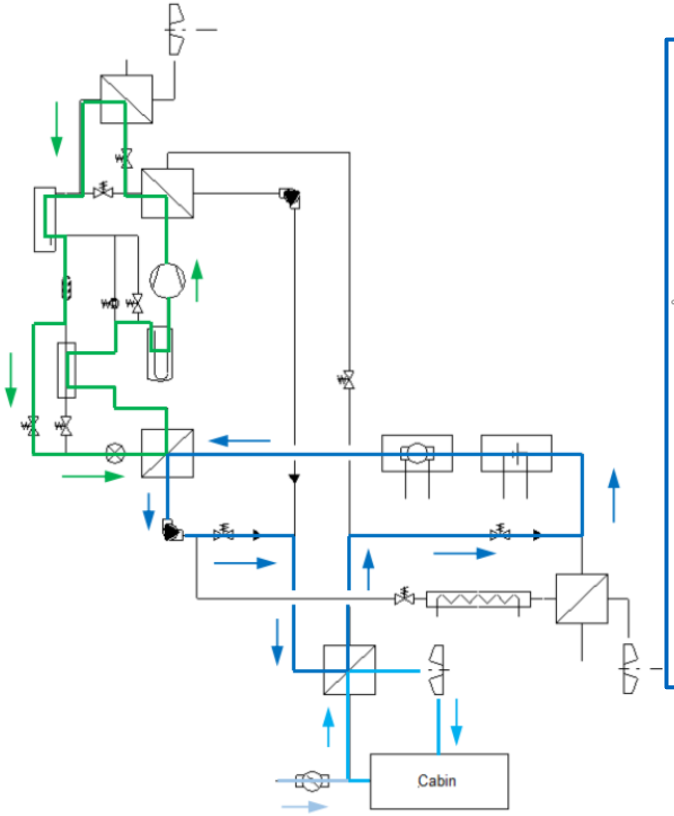
- The filling station is not equipped with compressors, it is necessary to have a pressure gradient between the tanks and the vehicle.
- This configuration is not able to utilize complete storage capacity. A certain residual pressure remains in the tanks, if the vehicle is filled to the target pressure.
- The division of storage into sections and usage of cascade filling affects the residual amount of hydrogen in empty storage.
- Sections can have different configuration. The number of sections increases the complexity of the management and increases the cost of the solution.
- Number of refuelings could increase substantialy.



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

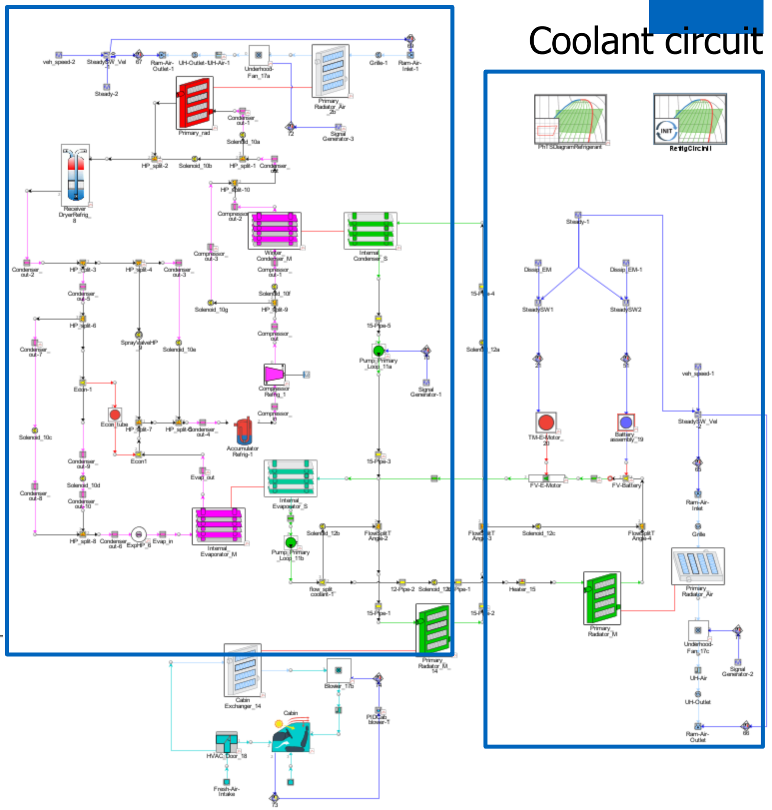
4-WP06-009 a 008: Model of advanced HVAC systems for BEV and PHEV

- elaboration of typical layout of system for starting simulation with organic fluent R1234 was finished last year
- Using collaboration with Skoda Auto and debugged model, the focus has been changed to preferred CO_2 (R744)
- **The software result was developed especially for better approximation of heat exchanger features with compact, low-Re elements.**



Refrigerant circuit

Coolant circuit

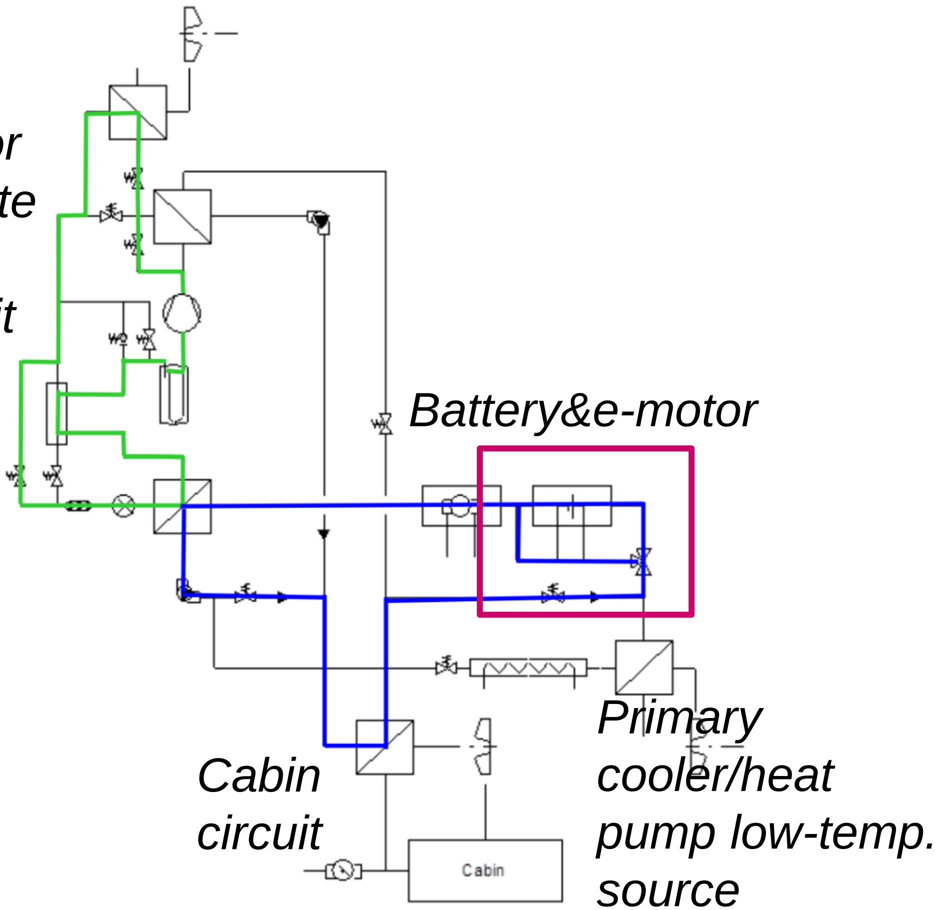


Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-009: Model of advanced HVAC systems for BEV and PHEV

- Model has been tranformed to new coolant R744 (CO_2)
- New compressor model (designed for R744) fed with measurement data from Škoda Auto
- Extremely high pressures (100-150 bar)
- Battery cooler bypass added to allow for more precise temperature control of battery module, and its partial uncoupling from cabin requirements during air conditioning (summer) operation
- Receiver dryer removed -> R744 circuit is almost supercritical

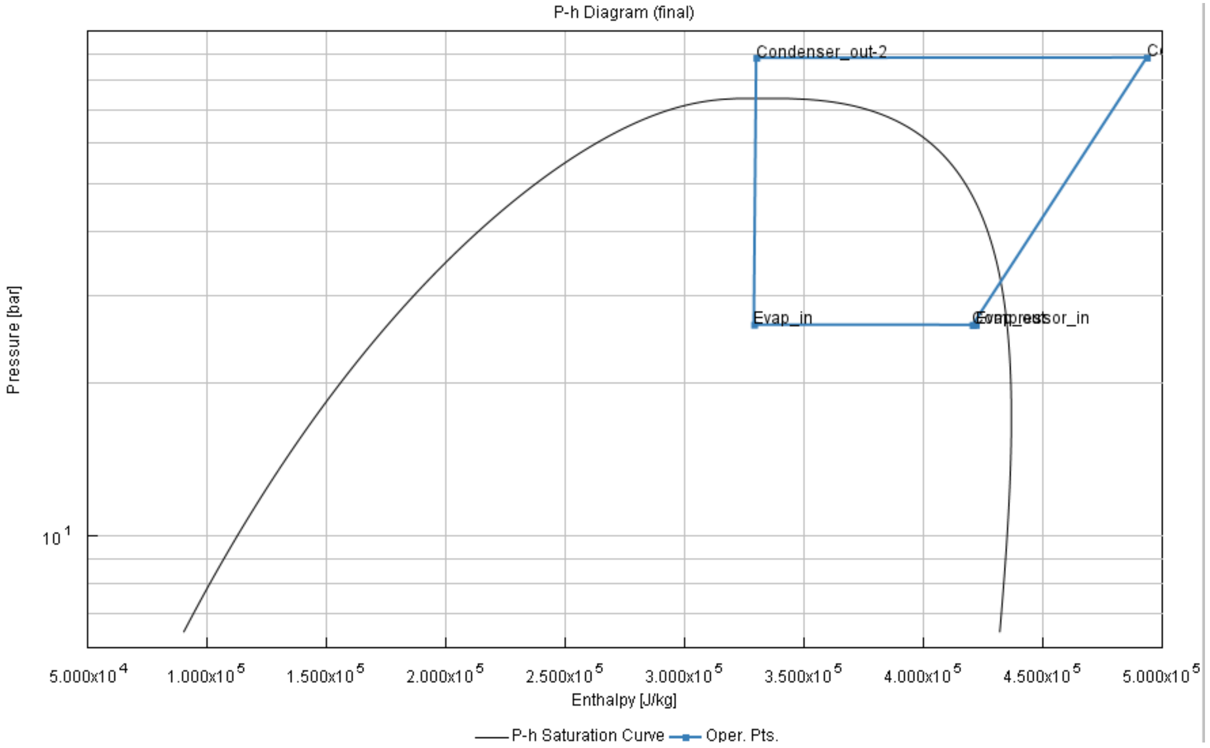
Reversible heat pump for heating (waste heat from electric circuit used) and cooling



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

4-WP06-009: Model of advanced HVAC systems for BEV and PHEV

- New compressor control adequate for R744 operation => compressor is regulated to maintain optimal discharge pressure
- Simulations of R744 show lower stability, specifically the Expansion module, causes divergent cases => this is dependent on chosen initial conditions (stable simulation should be invariant to initial conditions).
- Optimization planned to the next year requires stable operation.
- **Inadequate simulation of compact heat exchangers – new SW prepared to bridge this gap.**

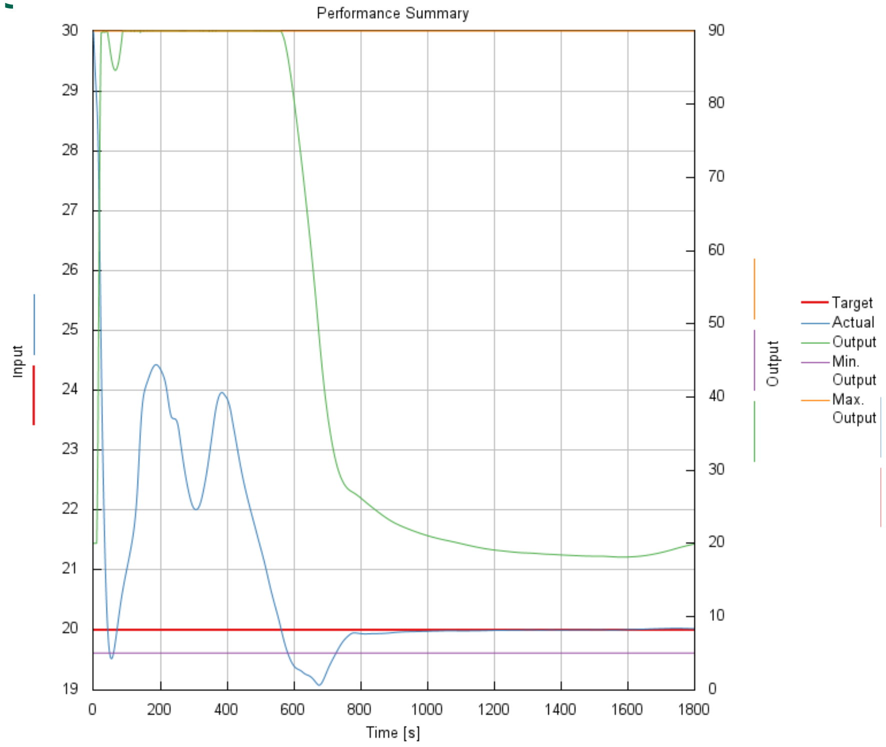


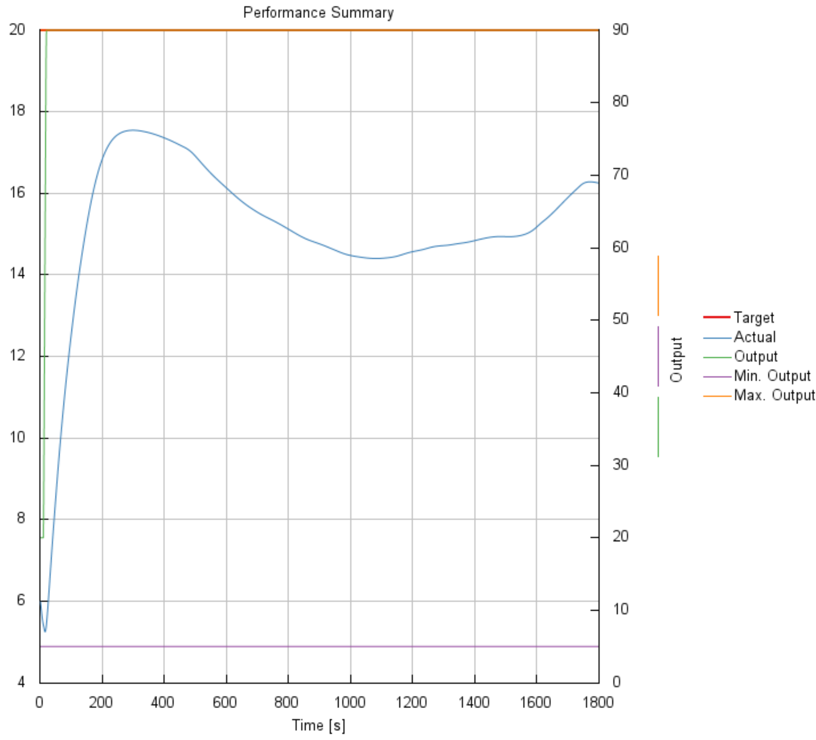
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-009: Model of advanced HVAC systems for BEV and PHEV

Results of system response during WLTC CYCLE - degC

- When using R744 the system is capable of maintaining required cabin temperatures during WLTC drive cycles
- Operation during high-speed charging still poses challenges for R744
- HeatPump performs better for cooling operation which is in accordance with the used medium.





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

Model is critically dependent on good simulation of compact heat exchangers, often equipped with heat transfer enhancement and different level of mixing among flow threads. **The goal of R-SW result is focused on this challenge**.

Real combined flow HE has to be corrected to mixing and changing countercurrent – cross – parallel flow patterns.

Correction countercurrent cross-flow: for A with full mixing crossing the flows of B in n serial cross-flows and full mixing between them. Example for n=4.

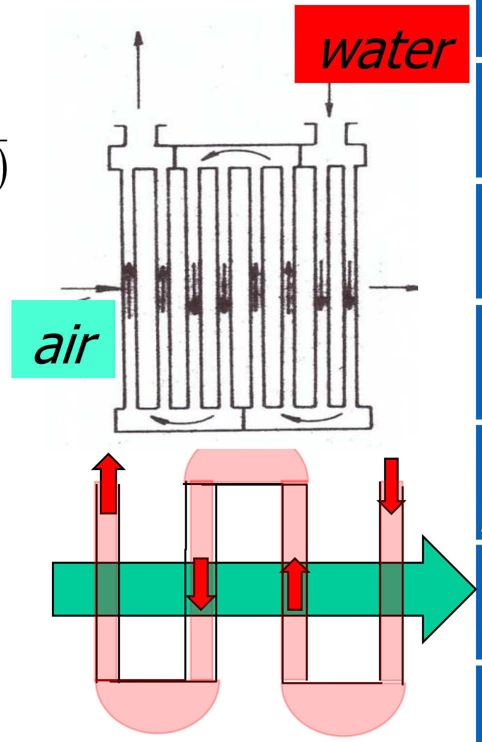
Instead of integral corrections**, Finite module HE model has been prepared.**

$$\frac{t_{A1}-t_{A2}}{t_{B2}-t_{B1}} = R = \frac{\dot{C}_B}{\dot{C}_A} \qquad \frac{t_{B2}-t_{B1}}{t_{A1}-t_{B1}} = P$$

$$\dot{C}_B\left(t_{B2}-t_{B1}\right) = kS\,\frac{t_{A1}-t_{B2}-\left(t_{A2}-t_{B1}\right)}{\ln\left(t_{A1}-t_{B2}\right)-\ln\left(t_{A2}-t_{B1}\right)}$$

$$\psi = \frac{\ln\dfrac{1-P}{1-RP}}{n\left(1-R\right)\ln\left(1+\dfrac{1}{R}\ln\dfrac{R-1}{R\left(\dfrac{1-P}{1-RP}\right)^{\frac{1}{n}}-1}\right)}$$

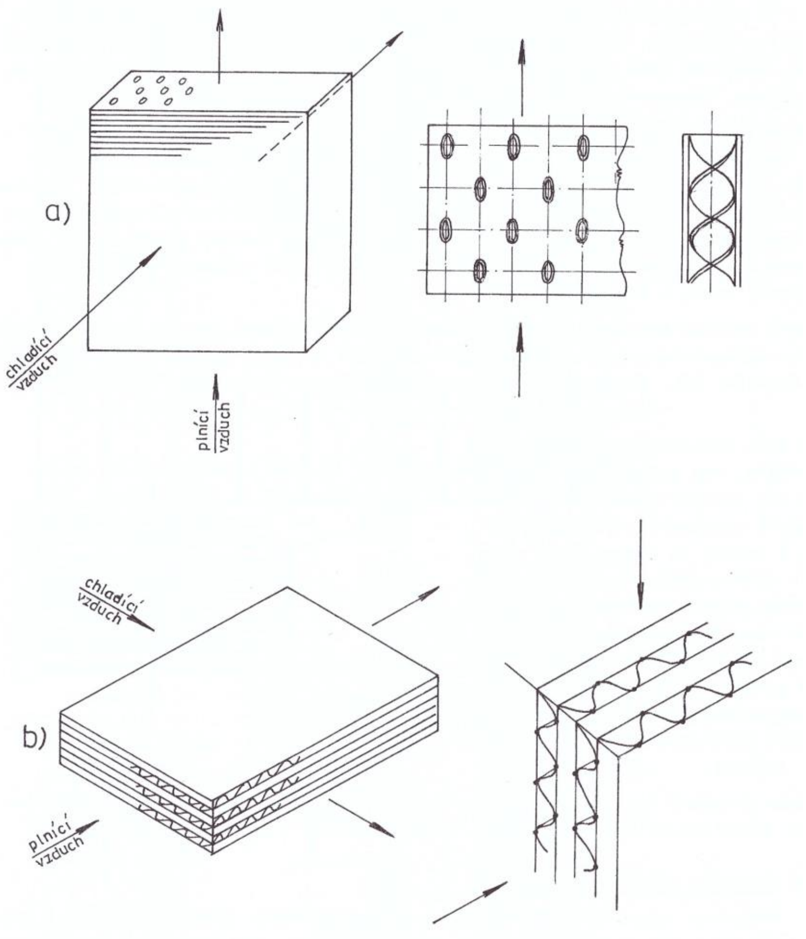
$$If \quad R=1:\psi = \frac{P}{n\left(P-1\right)\ln\left(1-\ln\left(1+\dfrac{P}{n\left(1-P\right)}\right)\right)}$$



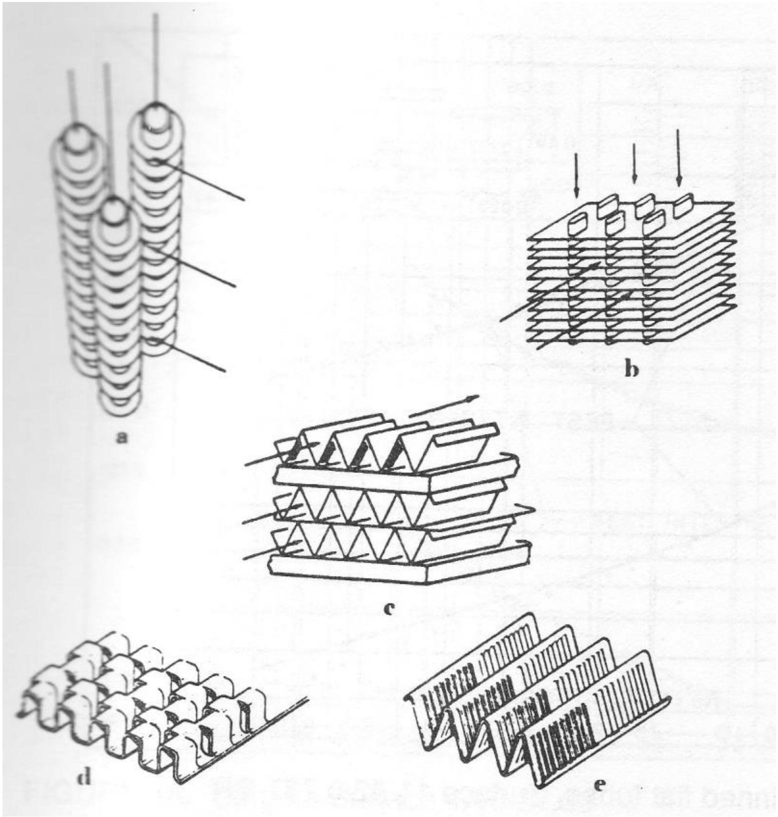
Heat Exchanger Surfaces Designed for Intensification of Heat Transfer

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



Finned surfaces, combined cross and parallel or countercurrent flows along pipe bunches or turbulization and boundary layer reducing measures mix flows from individual finite modules. These effects have to be considered in the model.



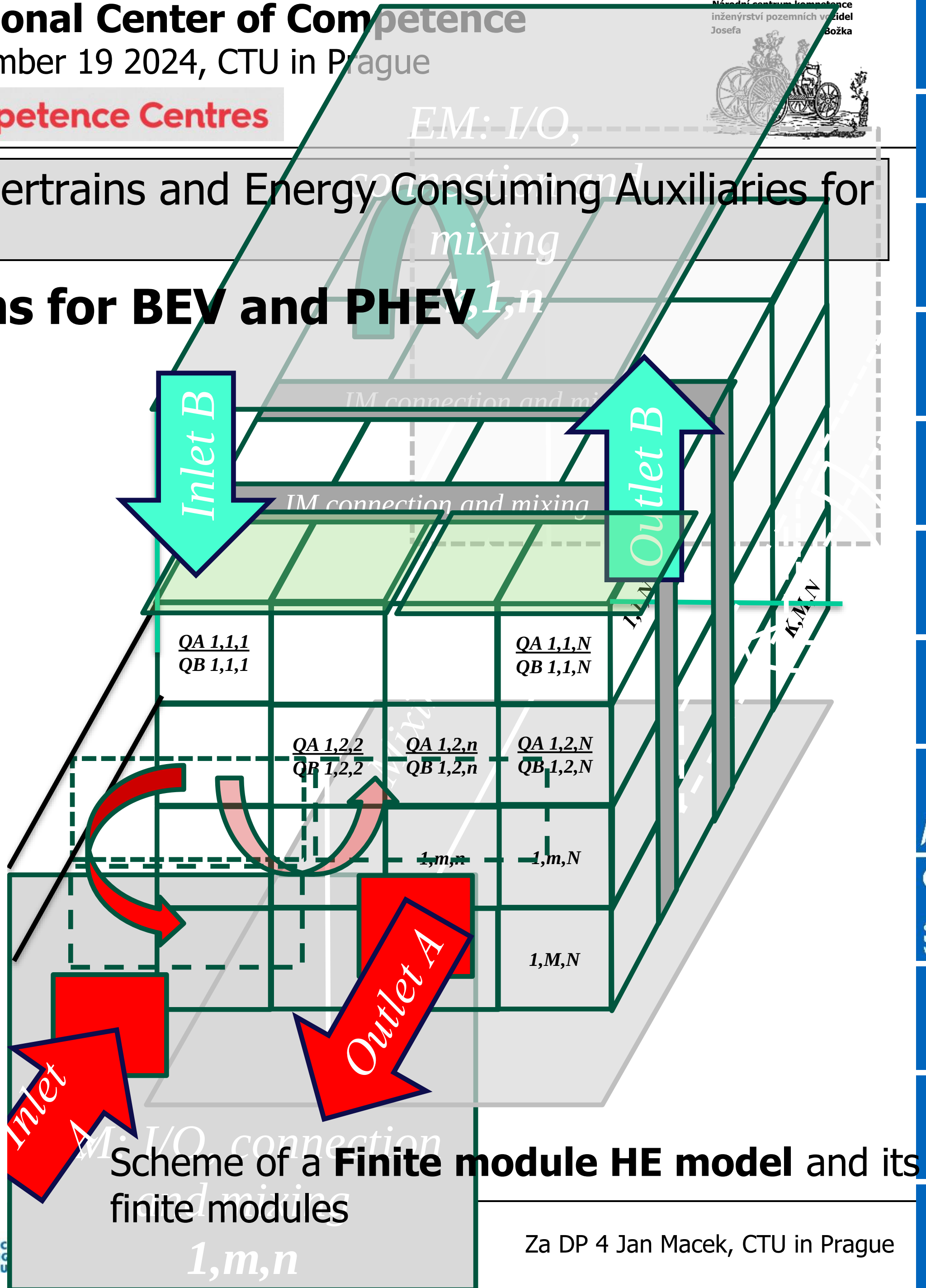
Examples of finned surfaces Kays W.M., London A.L.: Compact Heat Exchangers. McGraw-Hill, New York 1984

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

Finite module HE model

- Space position of a finite module: Three indices - coordinates for any thermal module QA, QB of either A or B fluid, namely k ... 1-K, m ... 1-M and n ... 1-N
- Three types of interface modules:
  - external EM with defined position of inlet(s) – start of flow progress coordinates either **a** or **b=1** – and outlet(s); possible change of direction of flow and pre-defined mixing among connected passages
  - internal IM connecting passages in the direction of flow progress coordinate and pre-defined mixing
  - thermal wall module (not drawn) between any QA and QB module of the same coordinates: thermal module considers the direction of both passages in contact, i.e., parallel, countercurrent or cross flow as defined by hand.
- Two "planar" coordinates define the position of passages for A and B; the position in the passage is defined by flow progress coordinates **a** or **b** assigned to the remaining space coordinate in direction of flow and the number of passage.
- Flow progress coordinate **a** or **b** increases by 1 passing Q module (EM or IM) and if limit of space coordinate, i.e., **K** for A or **M** for B is reached, the passage number is increased by 1 .



Scheme of a **Finite module HE model** and its finite modules

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

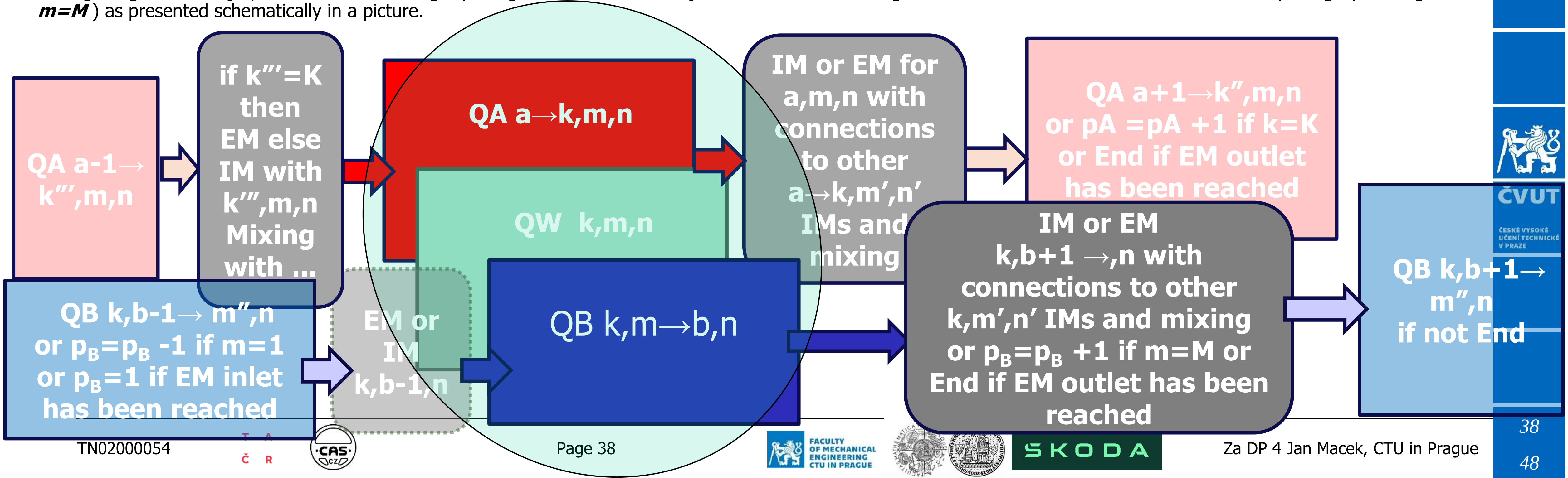
4-WP06-008: Model of advanced HVAC systems for BEV and PHEV: Finite module HE model

- Matrices k*m*n of thermal modules – QA at higher temperature fluid A, conduction in solid wall and transmittance QW and QB of lower temperature fluid B are available. QA, QW and QB are connected for the same space coordinates but the temperature inlet connections from previous QX are still missing.
- For QA, ***k*** is assigned to the flow progress coordinate ***a*** by passage number p_A (=1 for the first passage from EM inlet to the first EM return)

k = if p_A is odd then $a-K*(p_A-1)$ else $p_A*K+1-a$
and IM or EM modules can be assigned to ***a*** along A passage.

- For QB of the same ***k*** *and* **m**, flow coordinate ***b*** must be found. Starting with passage p_b

m = if p_B is odd then $b-M*(p_B-1)$ else $p_B*M+1-b$
Having assigned ***m*** to QBs, the connections along B passage can be found and QB can be connected using ***b*** coordinates with IM or EM at the ends of B passage (reaching ***m=1*** or ***m=M***) as presented schematically in a picture.

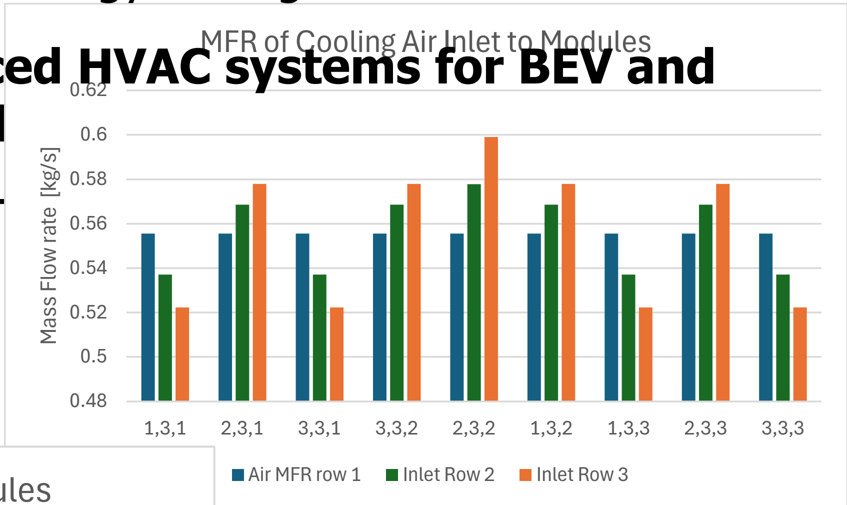


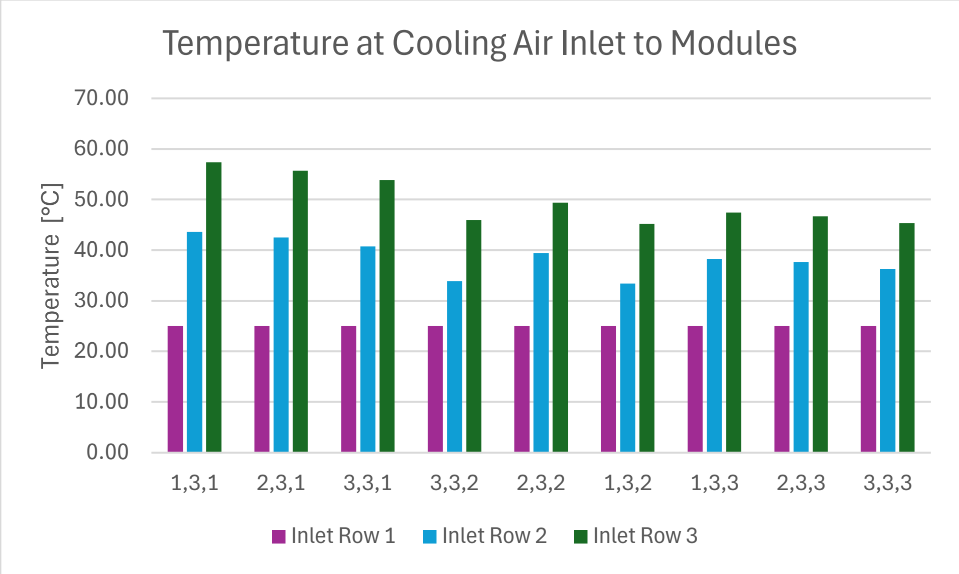
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

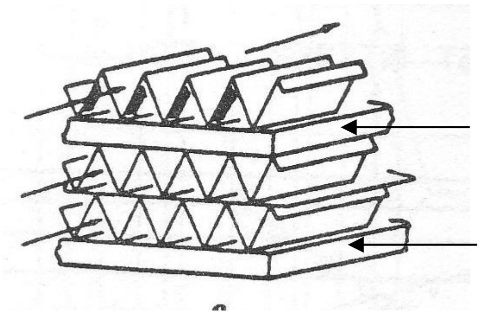
4-WP06-008: Model of advanced HVAC systems for BEV and PHEV: Finite module HE model

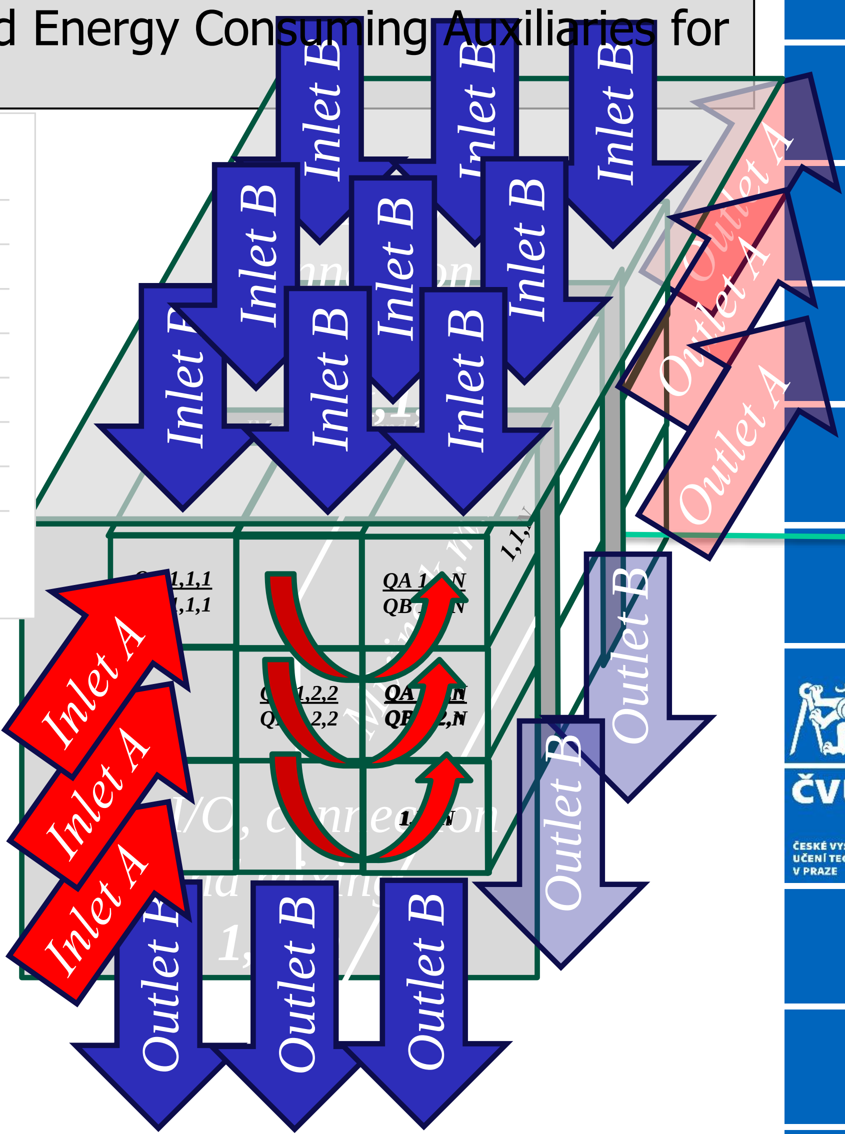
Tested heat exchanger 3*3*3 - multiple cross flow

- A ... cooled liquid
- B ... cooling air









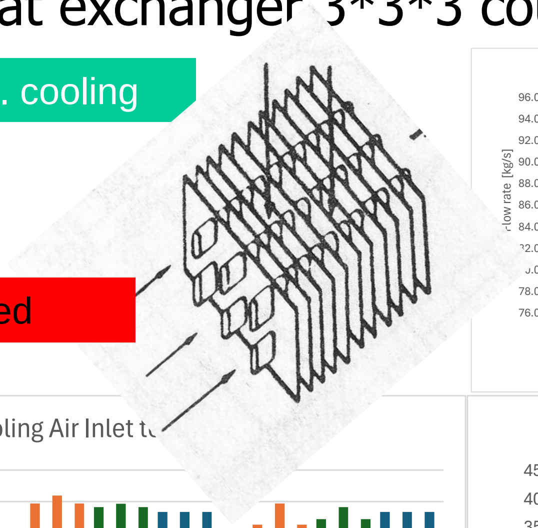
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

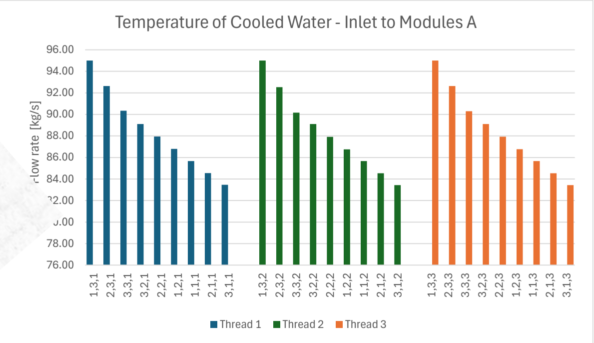
4-WP06-008: Model of advanced HVAC systems for BEV and PHEV: Finite module HE model

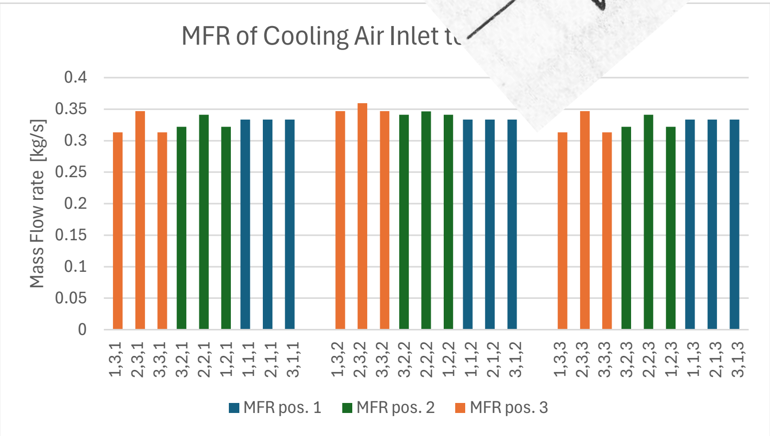
Tested heat exchanger 3*3*3 countercurrent cross flow

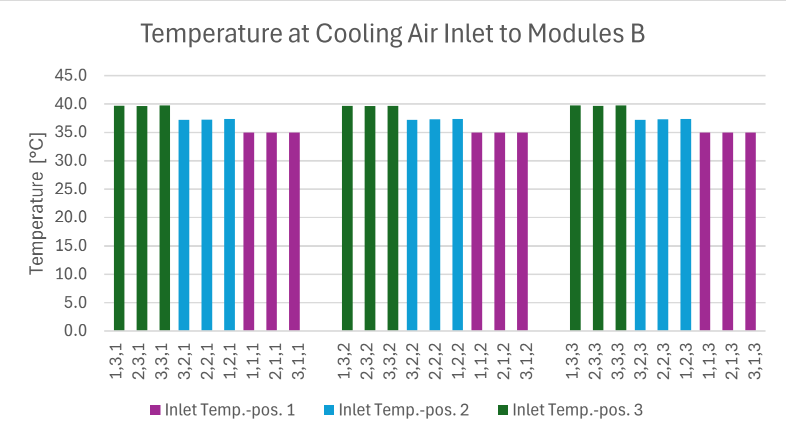
B ... cooling

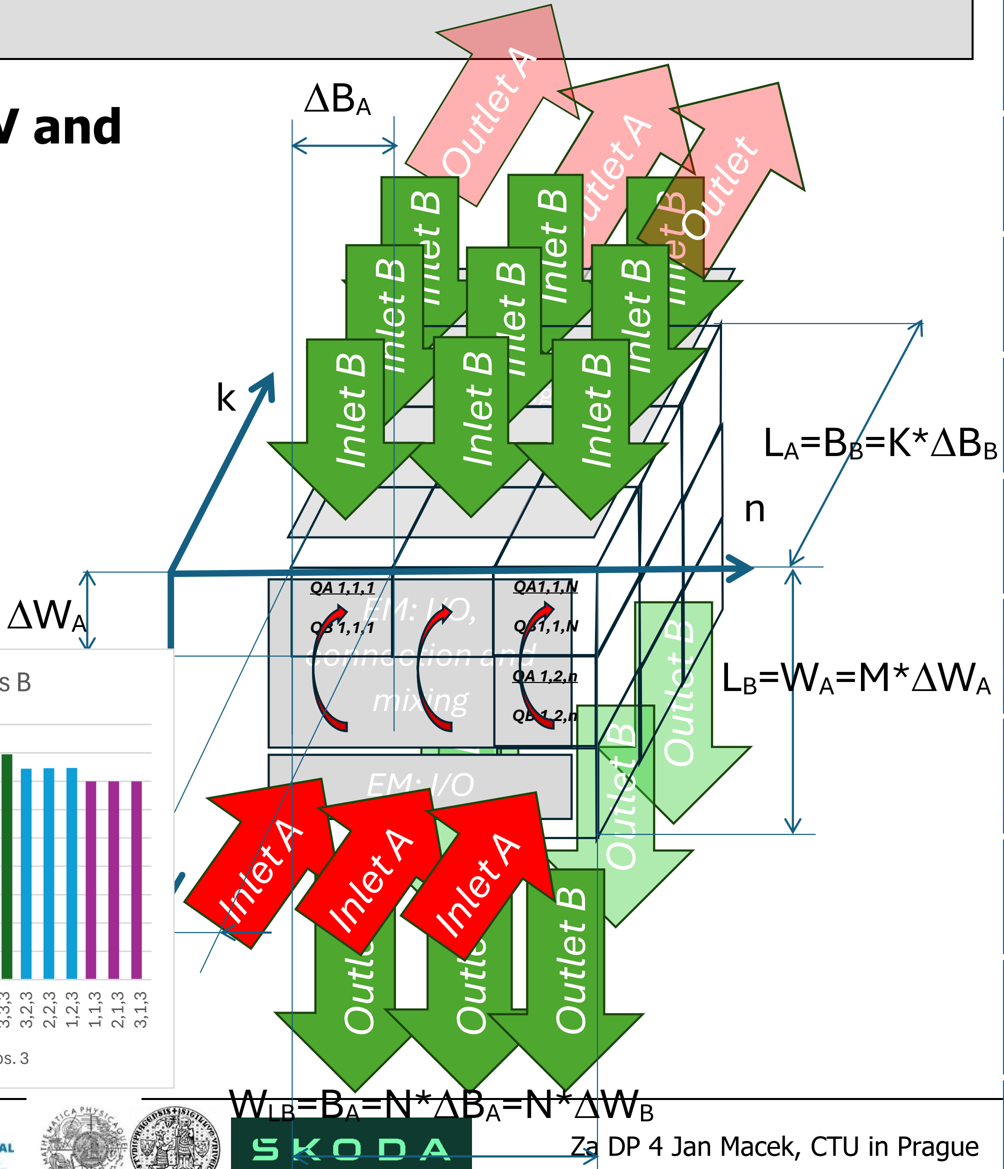
A ... cooled liquid











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

- **Deliverable** 4-WP06-008: Model of advanced HVAC systems for BEV and PHEV R-software CTU FME+Škoda Auto **due till 6/2024 4-WP06-008: Model of advanced HVAC systems for BEV and PHEV R-software CTU FME+Škoda Auto fulfilled by development of Heat Exchanger Finite Module code Heat_General_Model_v10.xlsx (currently 64 modules, 2 MB) in connection with GT Suite models for R744**
- **Deliverable** 4-WP06-001: Simulation of highly humid air expansion R-software CTU FME+CU FMP elaborated as a regression model based on integration of differential equations for adiabatic irreversible expansion or compression as ExpansionHumidGasPEMFC_v3.xlsx (3.6 MB) for connection with in-house turbine, ejector and heat exchanger 1D models and with GT Suite.
- **Deliverable** 4-WP06-011: Equipment for electrochemical measurement of gas permeability Fuzit-Registered model (Užitný vzor) CU FMP achieved.

The general goal, holistic approach to development, assessment and optimization of new powertrain components according to needs of industrial partners (Škoda Auto, and newly PBS Turbo and Garrett Advanced Motion) are fulfilled.

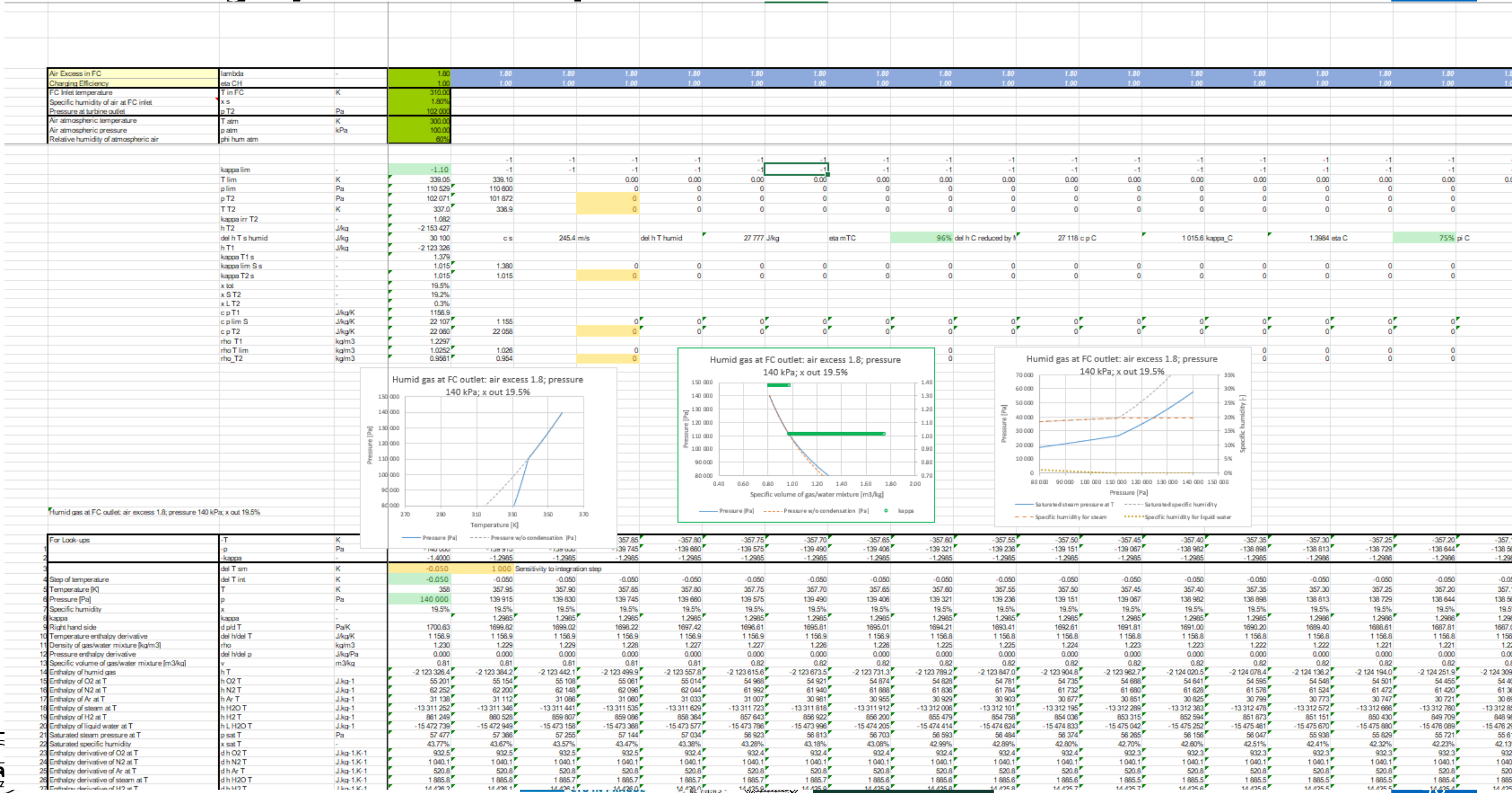
Deliverables of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-001: Simulation of highly humid air expansion – R SW

Integration of DE for pressure-temperature dependence.

Turbine total-to-static efficiency was corrected to outlet velocity change due to condensation of water – density increase of humid air mixture.

New tabulated data approach, collecting the pre-calculated results of differential equation integration expansion of humid gas and interpolation in data by regression model has been developed.



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

4-WP06-011: Equipment for electrochemical measurement of gas permeability Fuzit- Registered model (Užitný vzor) CU FMP

Úřad průmyslového vlastnictví

zapsal podle § 11 odst. 1 zákona č. 478/1992 Sb., v platném znění, do rejst

UŽITNÝ VZOR

číslo

37955

na technické řešení uvedené v přiloženém popisu.

Číslo zápisu: **37955**	Datum zápisu: 25.06.2024
Číslo přihlášky: **2024-41898**	Datum přihlášení: 12.04.2024
MPT: *G 01 N 15/08*	(2006.01)
Název:	Zařízení pro elektrochemické měření propustnosti plynů
Majitel:	Univerzita Karlova, Praha 1, Staré Město LEANCAT s.r.o., Praha 7, Holešovice
Původce:	Mgr. Yurii Yakovlev, Ph.D., Praha 9, Střížkov Mgr. Alina Madalina Darabut, Praha 9, Libeň Yevheniia Lobko, Ph.D., Praha 9, Střížkov prof. Mgr. Iva Matolínová, Dr., Zdiby, Brnky prof. RNDr. Vladimír Matolín, DrSc., Zdiby, Brnky

V Praze dne: 25.06.2024 Za správnost:

Jiří Voráček
oddělení rejstříl

Úřad průmyslového vlastnictví v zápisném řízení nezjišťuje, zda předmět užitného vzoru splňuje podmínky způsobilosti k ochraně podle § 1 zák. č. 478/1992 Sb.

Development of the new electrochemical method for measuring gas permeability of PEM fuel cell components

Deliverables 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

Finite Module for Heat Exchanger Model suitable for HVAC, waste heat and cooling systems

- Finite modules are prepared for
  - heat transfer and friction pressure loss module, separately for fluid A and B ... Q A, Q B
  - heat conductance and transmittance in thermally connecting modules for separating walls Q W, assigned to Q A and Q B by space position
  - external interfaces EM (inlets, outlets and change of flow direction with adjustable mixing);
  - internal interfaces IM defining connections from/to other finite module with adjustable mixing.
- Modules Q connect high temperature fluid A, wall W and low temperature fluid B. Heat transfer is governed heat transfer coefficient at both Q A and Q B modules together with Q W mean temperature difference; geometry of heat transfer surfaces is defined in them and criterial relations Nu=f(Re, Pr, geometry, ...) or St*Pr=f(Re, geometry) are used for heat transfer coefficients. Friction pressure loss is determined at both sides for A and B. Fluid material data are determined for mean temperature from Q W and mean pressure.
- Q W simulates thermal resistance of solid wall, heat transmittance coefficient and mean temperature difference. It is corrected using analytical relations for logarithmic temperature difference respecting type of flow in Q W module (parallel P, countercurrent CC or cross flow CR – it can change along the same passage in connected modules).
- Modules EM and IM define connections between either Q A or Q B modules. Transversal connection of Q W modules (heat conduction along flow splitting wall) is up-to-now not considered. Modules EM and IM use enthalpy conservation for adjustable mixing of flows from different passages/channels; local inlet pressure loss is predicted; material data are calculated for local temperature and pressure.
- Input of inlet MFR or inlet velocity and temperature in EMs may consider non-uniform flow field at inlet.

Dleiverables 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: Finite module HE model

- Heat transfer using St, pressure drop using C_f

$$St\,\mathrm{Pr}^{2/3} = f_\alpha(\mathrm{Re}_{r_h}) = f_\alpha\left(\frac{4r_h\dot{m}}{A\mu}\right) = \frac{\alpha A}{c_p\dot{m}}\mathrm{Pr}^{2/3} = \frac{\alpha}{c_p\mu\mathrm{Re}}4r_h\,\mathrm{Pr}^{2/3}$$

$$C_f = f_f(\mathrm{Re}_{r_h}) = \frac{\Delta p}{\frac{1}{2}\rho w^2\frac{L}{r_h}}$$

$$r_h = \frac{AL}{S} = \frac{A}{O} = \frac{d_h}{4}$$

$$\frac{\dot{m}}{A} = \mathrm{Re}\frac{\mu}{4r_h}$$

$$\alpha = \frac{\mu c_p}{\mathrm{Pr}^{2/3}}\mathrm{Re}\frac{1}{4r_h}f_\alpha$$

$$\alpha[W.m^{-2}.K^{-1}] = \frac{\mu c_p}{\mathrm{Pr}^{2/3}}\mathrm{Re}\frac{1}{4r_h}f_\alpha$$

$$E[W.m^{-2}] = \frac{\Delta p}{\rho}\frac{\dot{m}}{S}\frac{A}{A} = \frac{1}{2}C_f\frac{L}{r_h}\rho\left(\frac{\dot{m}}{A\rho}\right)^2\frac{\dot{m}}{\rho A}\frac{r_h}{L} = \frac{1}{2}\left(\frac{\mu^3}{\rho^2}\right)\left(\frac{1}{4r_h}\right)^3\mathrm{Re}^3 f_f$$

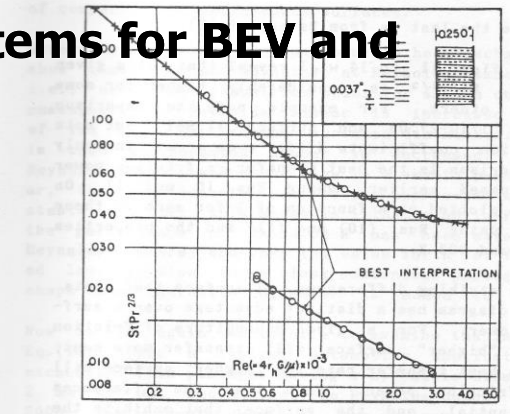


FIGURE 13. Strip-fin Surface 1/10-27.03

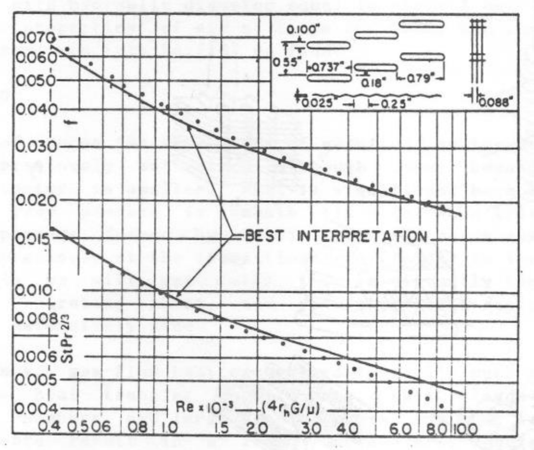


FIGURE 11. Finned flat tubes, Surface 11.32-0.737-SR

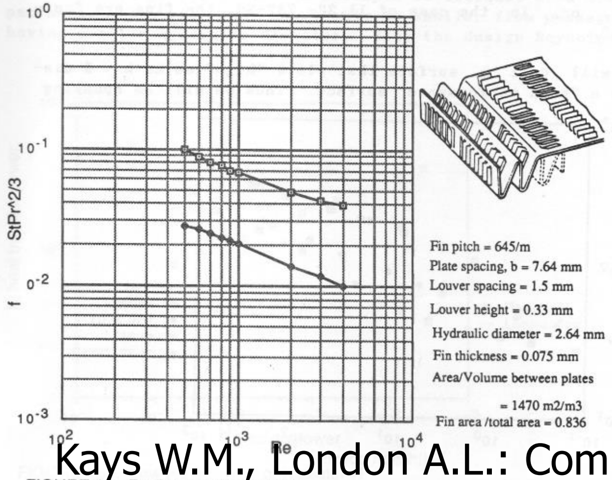


FIGURE 14. Radiator-H (Davenport)

Kays W.M., London A.L.: Compact Heat Exchangers, McGraw-Hill, New York 1984

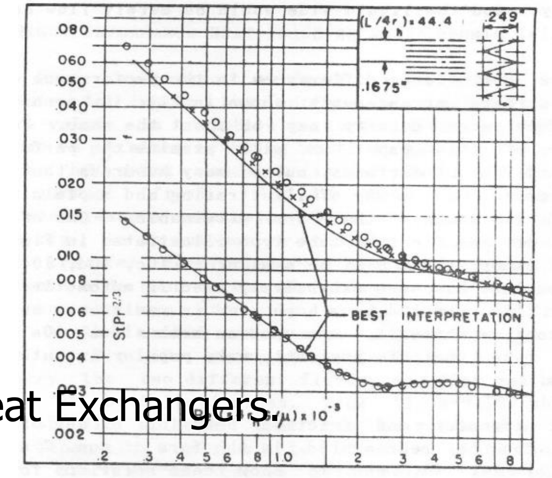
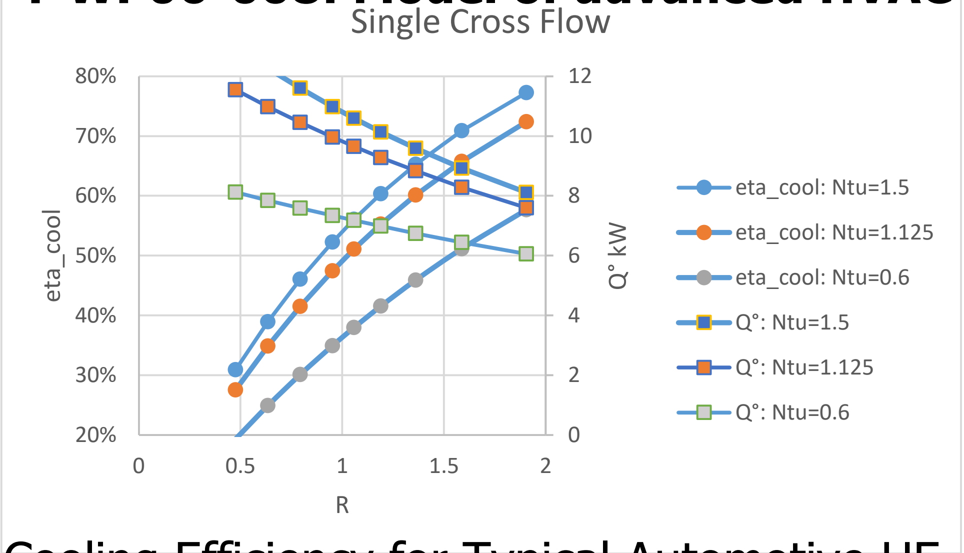


FIGURE 12. Plain plate-fin Surface 11.94T

Deliverables 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: Finite module HE model

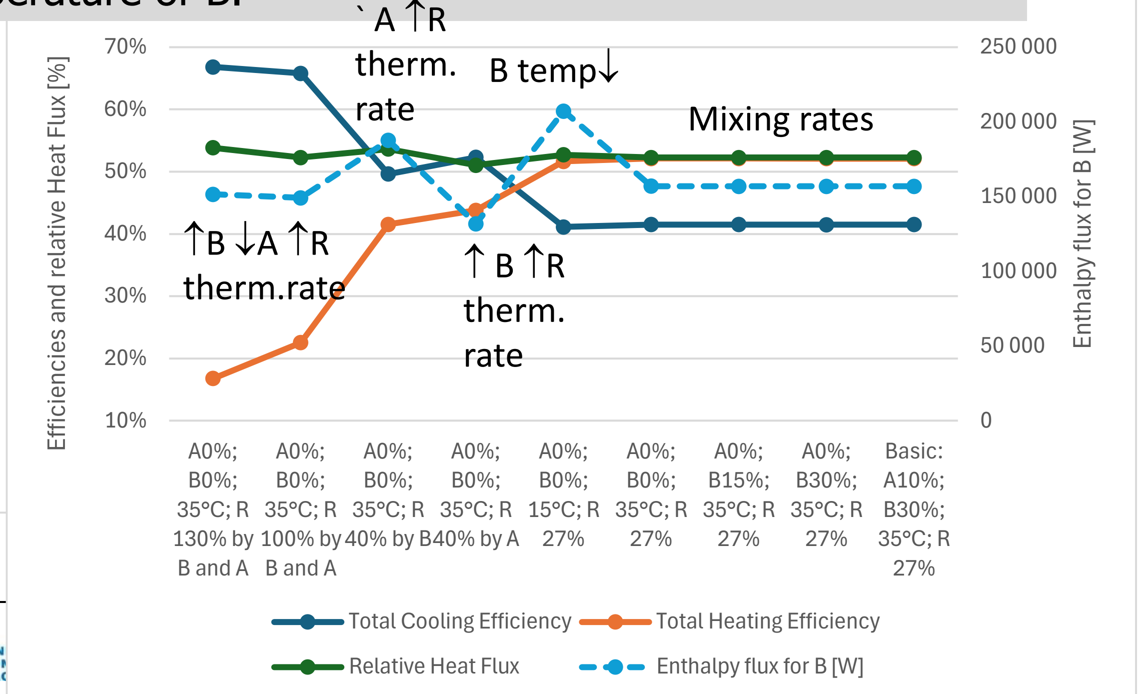


Cooling Efficiency for Typical Automotive HE

Single cross-flow typical for radiator (primary air-to-liquid underhood cooler). Countercurrent cross-flow typical for larger compressed air – liquid intercoolers, although air-to-air single cross flow is used for car and truck engines, as well.

High cooling efficiency considers high temperature decrease, which is the goal in some cases only – e.g., for compressed air cooling. Highest thermal flux needs low cooling efficiency, which ensures high temperature difference between A and B.

Example of test cases with mixing rates for A and B, R=B/A ratio of thermal capacity rates (changed by A or B or both) and the lowest temperature of B.

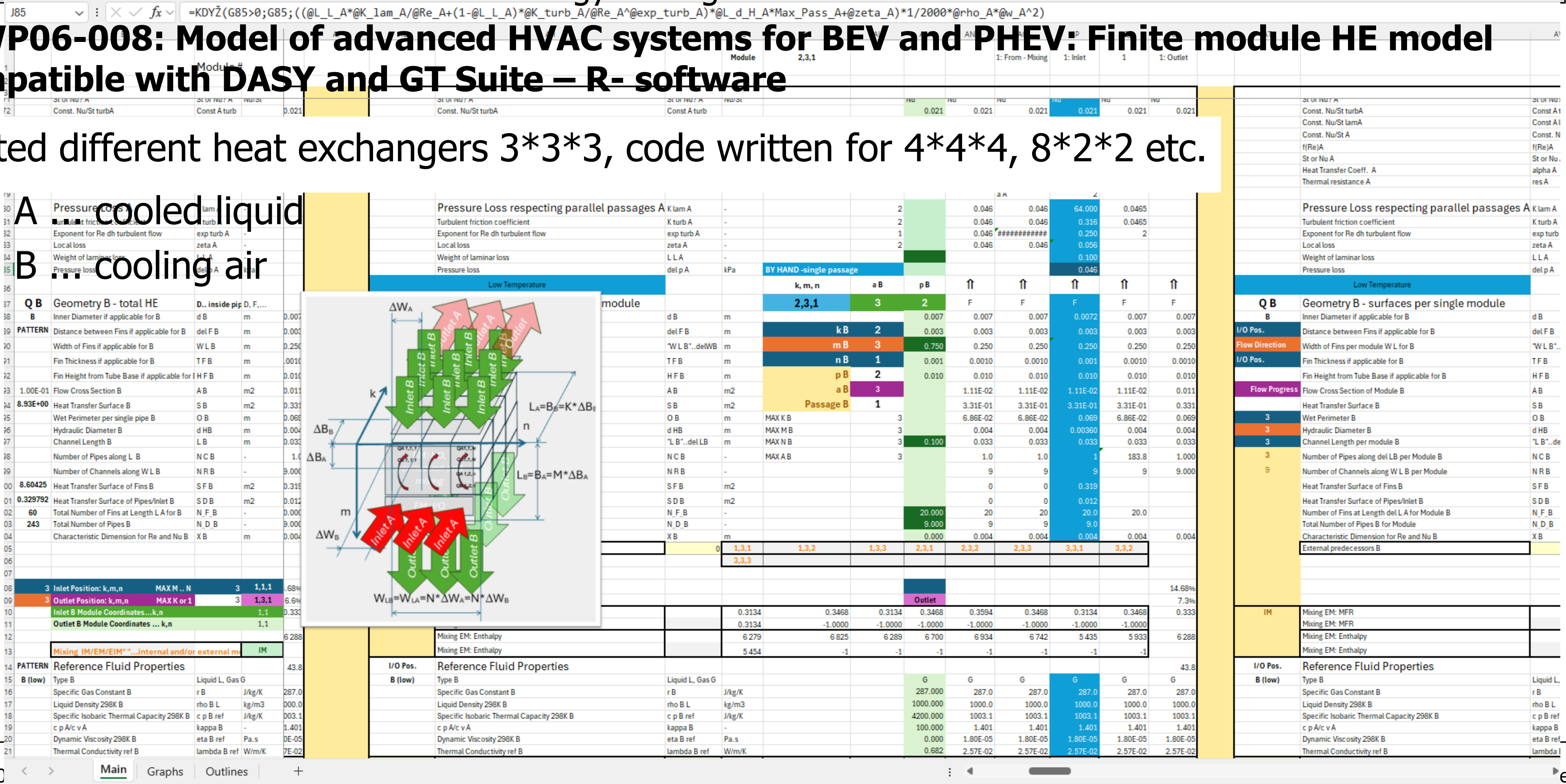


Deliverables of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

4-WP06-008: Model of advanced HVAC systems for BEV and PHEV: Finite module HE model compatible with DASY and GT Suite – R- software

Tested different heat exchangers 3*3*3, code written for 4*4*4, 8*2*2 etc.

- A … cooled liquid
- B … cooling air



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 (Heat Exchanger Finite Module code Heat_General_Model_v10.xlsx) 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

Acknowledgment

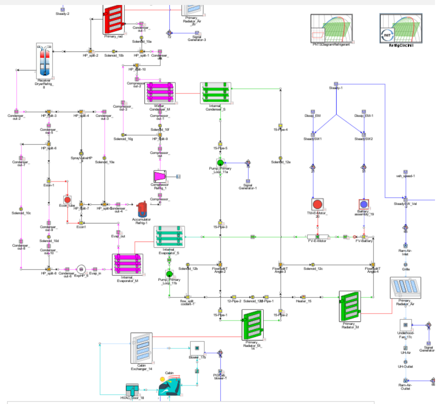
This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Centres II, project # TN02000054 Božek Vehicle Engineering National Center of Competence (BOVENAC).

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

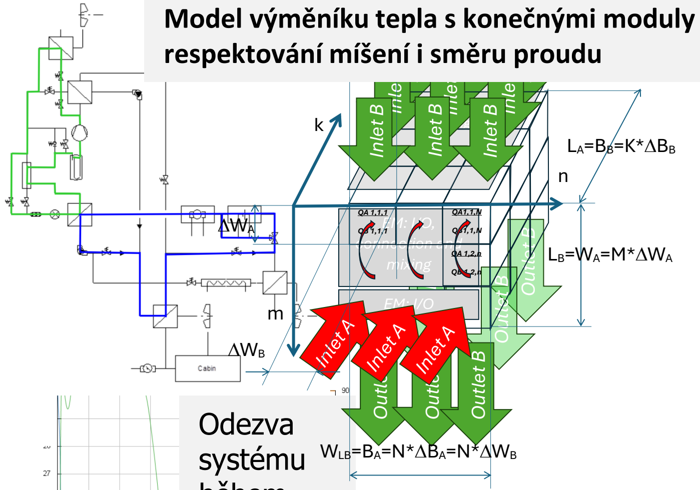
Děkuji Vám za pozornost a všem spolupracovníkům za vzornou spolupráci.

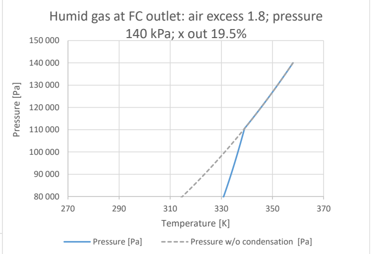
Výsledky 4-WP06 Alternativní hnací jednotky a energeticky náročná příslušenství vozidel: Palivové články a topné/klimatizační systémy v letech 2023-2025

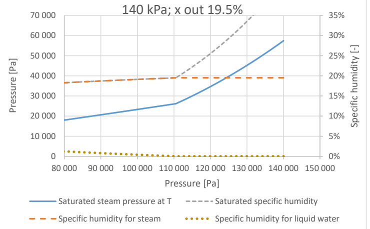
Pokročilé topné a klimatizační systémy pro bateriová a hybridní vozidla ČVUT FS + Škoda Auto – R1234 a R744



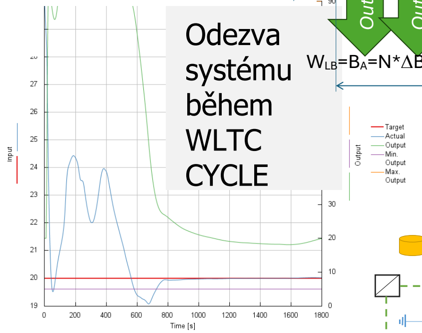
Model výměníku tepla s konečnými moduly pro respektování míšení i směru proudu

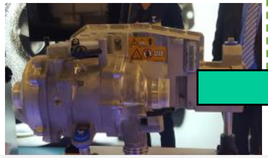


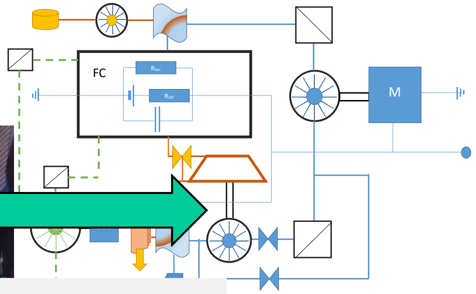




Odezva systému během WLTC CYCLE

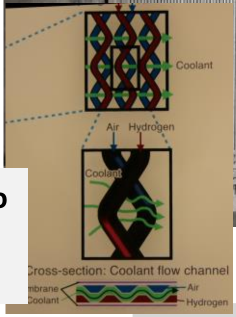






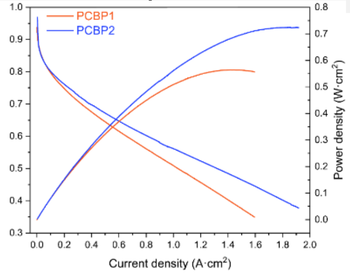
Zařízení pro katodu (vzduch) i anodu (H2) palivového článku s elektricky hnaným kompresorem nebo turbodmychadlem s expanzí vlhkého plynu – ČVUT FS

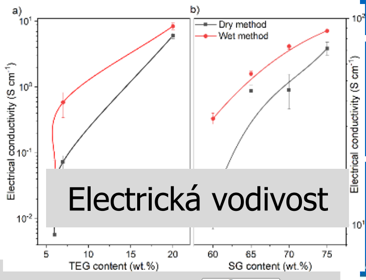
Nová elektrochemická metoda měření propustnosti plynů



Výrobní technologie pro neomezené tvarování bipolárních desek

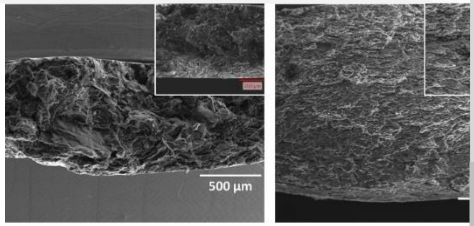
Vliv elektrické vodivosti na vlastnosti palivového článku

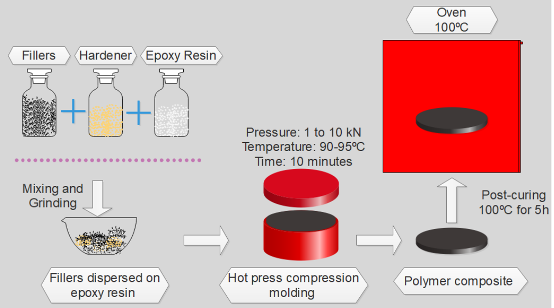




Electrická vodivost

Rozdíly mezi suchým a vlhčeným mícháním složek kompozitu



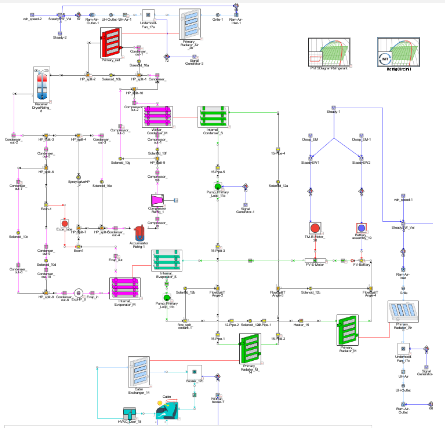


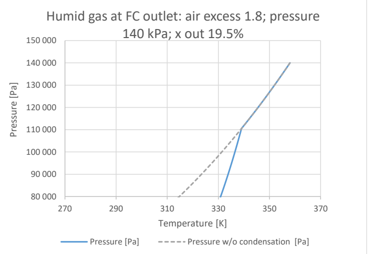
Bipolární desky z epoxidového polymeru s grafitovými nanočásticemi– MFF UK, I. Matolínová

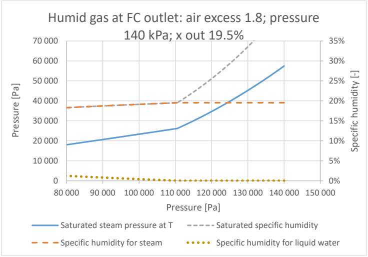
FAKULTA STROJNÍ ČVUT V PRAZE

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

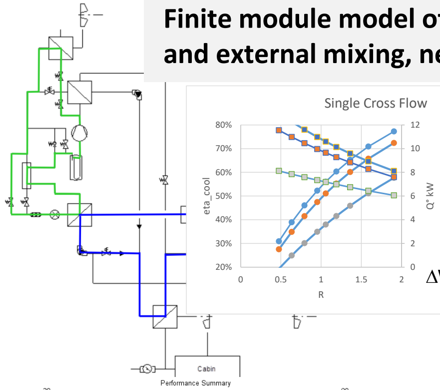
HVAC systems for BEV and PHEV – CTU FME + Skoda Auto R1234 and R744

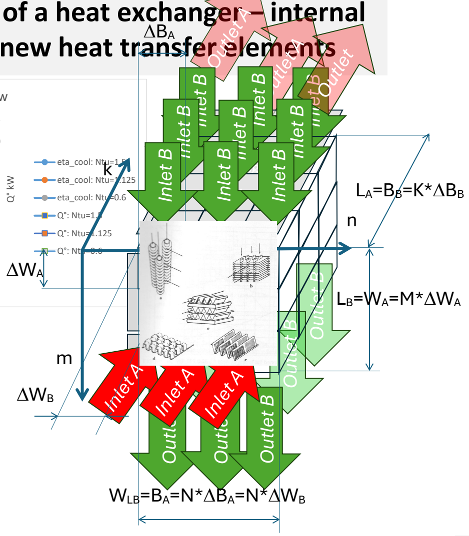




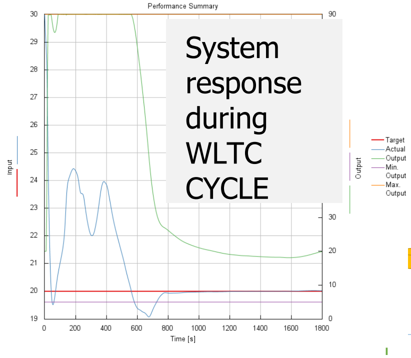


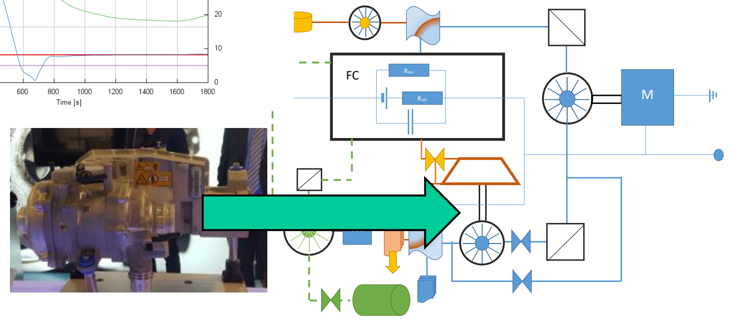
Finite module model of a heat exchanger – internal and external mixing, new heat transfer elements





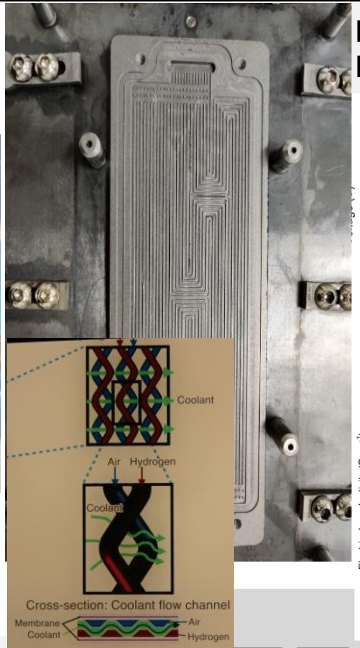
System response during WLTC CYCLE



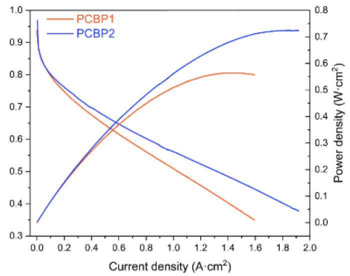


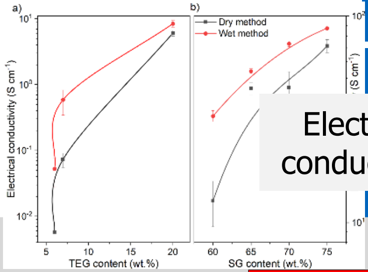
Air-loop and H2 loop devices for using pressurized air exhaust at PEM FCs with electrically supported compressors or TCs and humid gas – CTU FME, J. Macek

New electrochemical method for measuring gas permeability of PEM fuel cell components



Electrical conductivity effect on PEM fuel cell performance

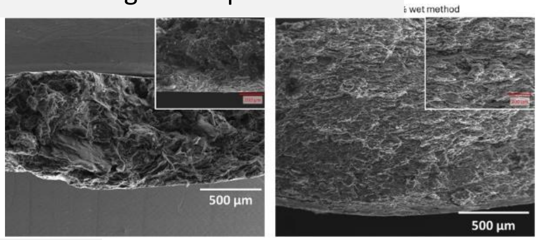


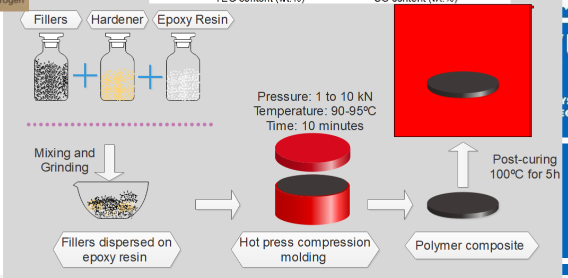


Electrical conductivity

Manufacturing technologies – free shaping of channels in bi-polar plates

Differences between dry and wet mixing of components



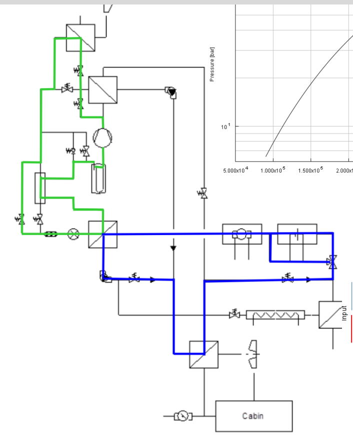


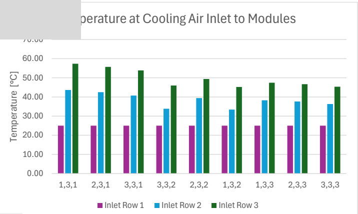
Polymer-composite Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite – MFF CU, I. Matolinova

ŠKODA

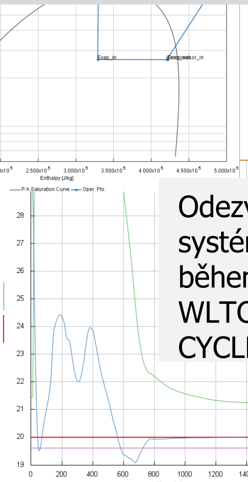
Výsledky 4-WP06 Alternativní hnací jednotky a energeticky náročná příslušenství vozidel: Palivové články a topné/klimatizační systémy za rok 2024

Pokročilé topné a klimatizační systémy pro bateriová a hybridní vozidla ČVUT FS + Škoda Auto – R744

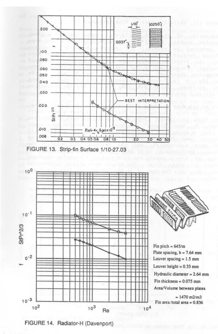


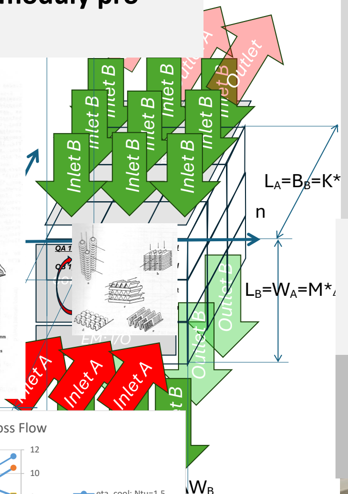


Odezva systému během WLTC CYCLE

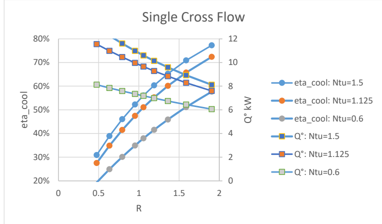


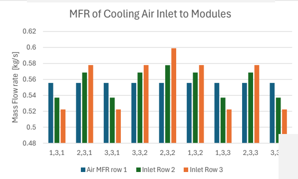
Model výměníku tepla s konečnými moduly pro respektování mísení i směru proudu

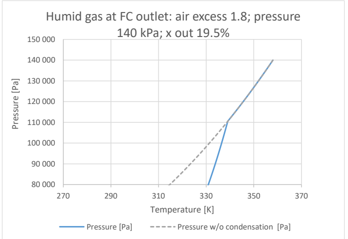


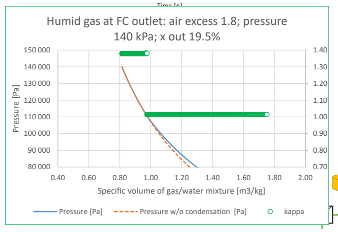


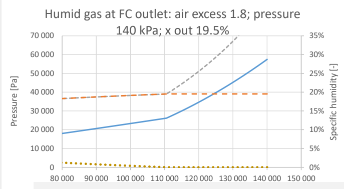
Průtokové a teplotní profily při směšování uvnitř výměníku podél tahů obou tekutin

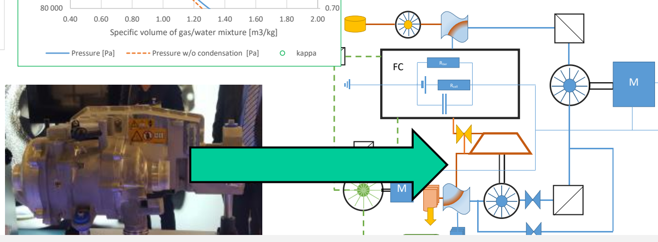




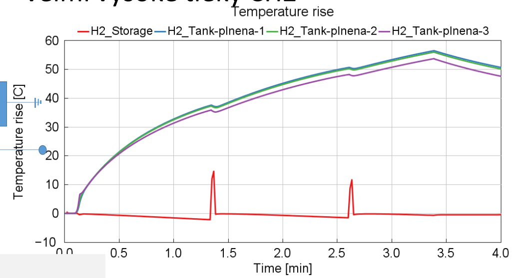




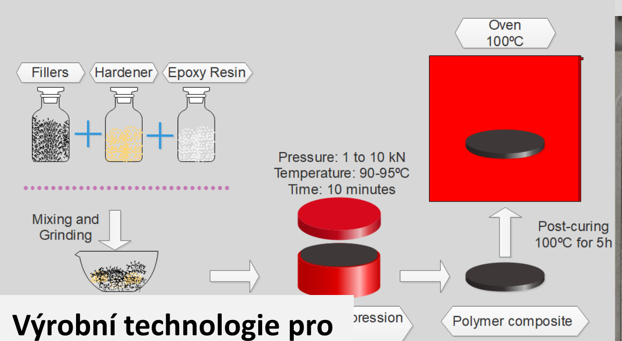




Strategie plnění tlakových zásobníků pro velmi vysoké tleky CH2



Zařízení pro katodu (vzduch) i anodu (H2) palivového článku s elektricky hnaným kompresorem nebo turbodmychadlem s expanzí vlhkého plynu – ČVUT FS J. Macek



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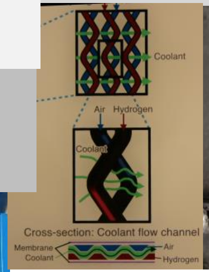

Nová elektrochemická metoda měření propustnosti plynů

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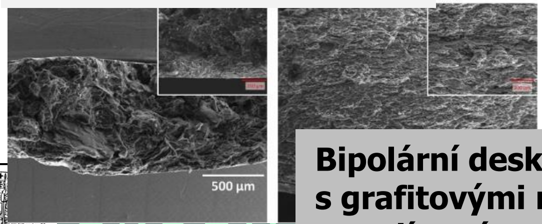

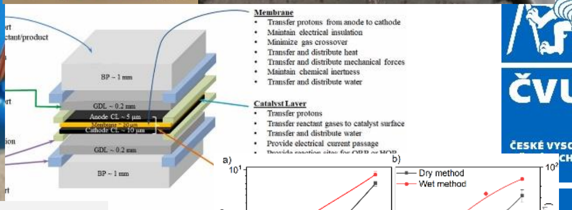

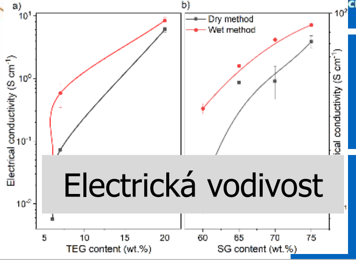

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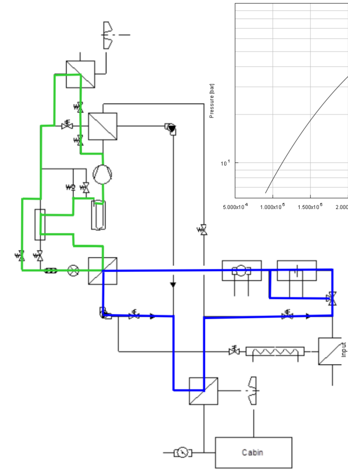
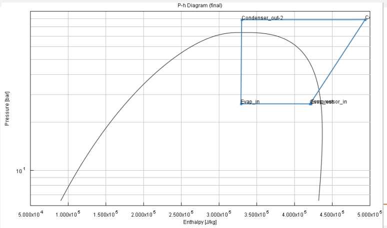
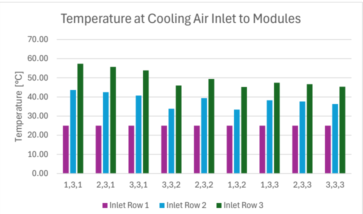
Bipolární desky z epoxidového polymeru s grafitovými nanočásticemi– MFF UK, I. Matolínová

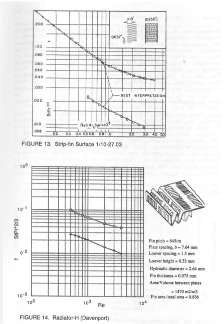
Results of 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management – Achieved 2024

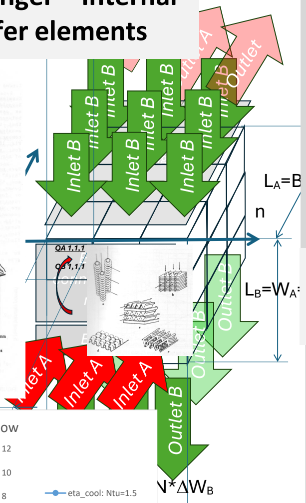
Advanced HVAC systems for BEV and PHEV – CTU FME + Skoda Auto – R744

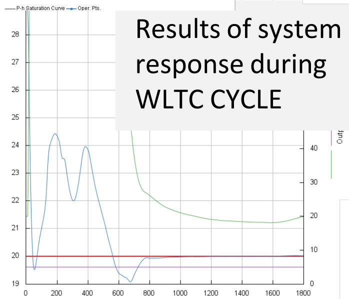
Finite module model of a heat exchanger – internal and external mixing, new heat transfer elements



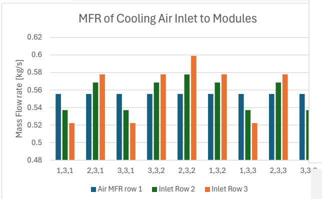


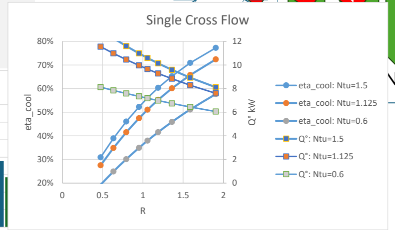


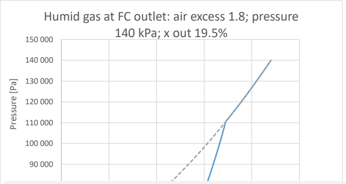
Results of system response during WLTC CYCLE

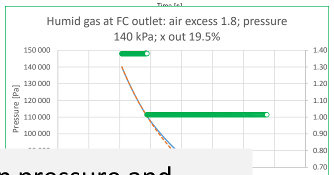


MFR and temperature profiles along path of cooling and cooled fluids

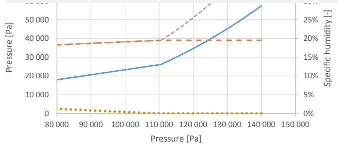


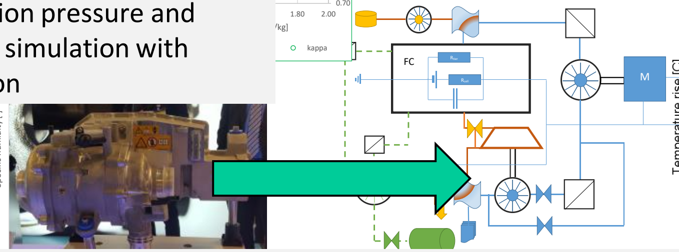






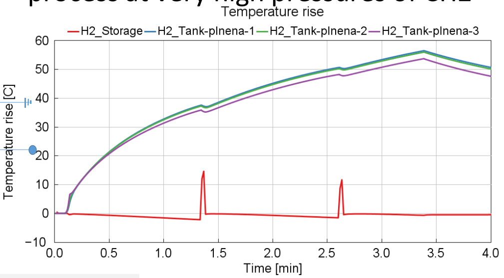
p-T, humidity and saturation pressure and isentropic exponent from simulation with partial steam condensation

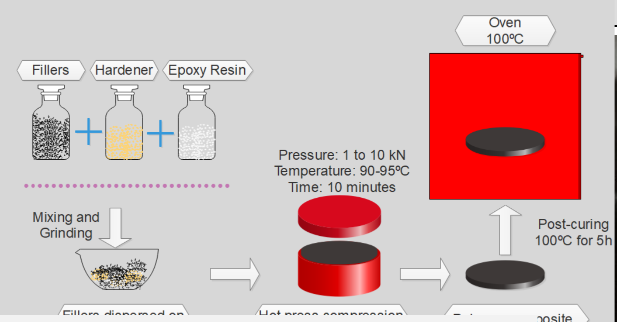




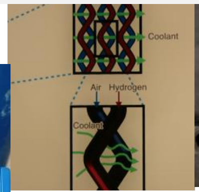
Air-loop and H2 loop devices for using pressurized air exhaust at PEM FCs with electrically supported compressors or TCs – CTU FME

Strategies for pressure cylinder filling process at very high pressures of CH2

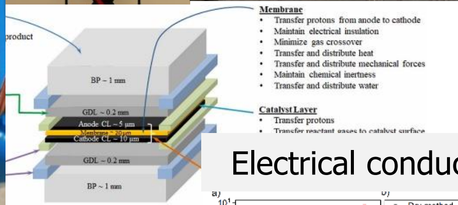




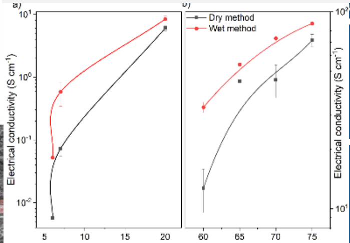
Manufacturing technologies – free shaping of channels in bi-polar plates

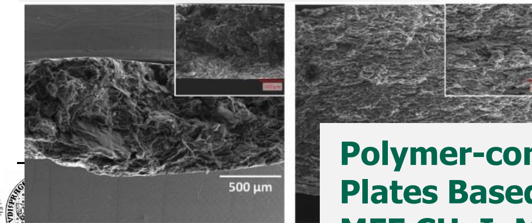
New electrochemical method for measuring gas permeability of PEM fuel cell components

Electrical conductivity



Differences between dry and wet mixing of components



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

Appendices to 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles

Appendices

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

2) Curing conditions: Differential Scanning Calorimetry

DSC thermograms of the epoxy resin system (prepolymer and hardener):

- *in its unheated state:*

- sharp endothermic peak at 46 °C corresponding to the melting temperature (Tm) of the prepolymer

- smaller endothermic peak around 65 °C attributed to the melting temperature of the hardener. - broad exothermic peak around 150 °C is assigned to the curing reaction. The onset of the curing reaction occurs around 80 °C, with completion at temperatures exceeding 200 °C.

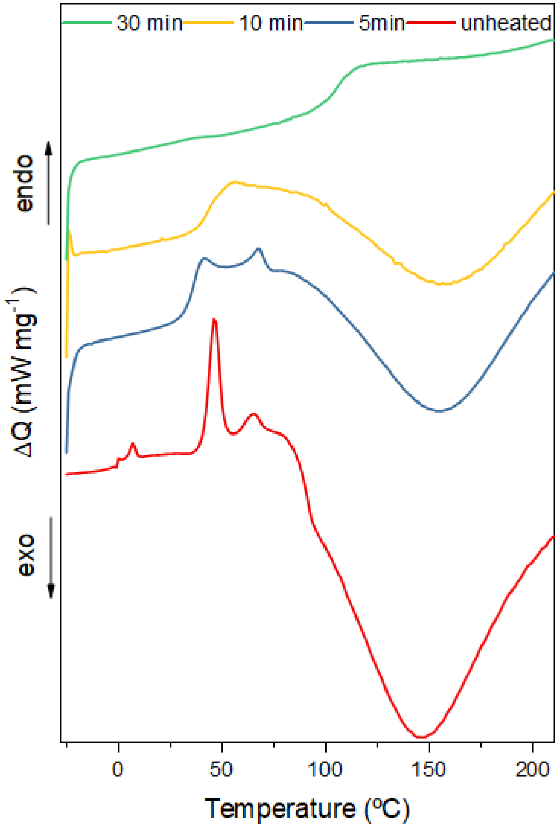
- *after heating at 150 °C for 5, 10 and 30 minutes:*

- glass transition temperatures (Tg) at different heating times: Tg (5min) = 36 °C, Tg (10min) = 44 °C, Tg (30min) = 105 °C, indicating a significant improvement in the glass transition temperature with extended curing time.

- after 30 minutes of heating (green line), the absence of an exothermic peak suggests complete curing of the polymer.

The curing reaction begins at 80 °C, reaches its peak at 150 °C and is fully completed after 30 minutes at 150 °C.

For the processing of the polymer and its composites, the optimal parameters are at temperatures of 120 °C for 40 minutes.

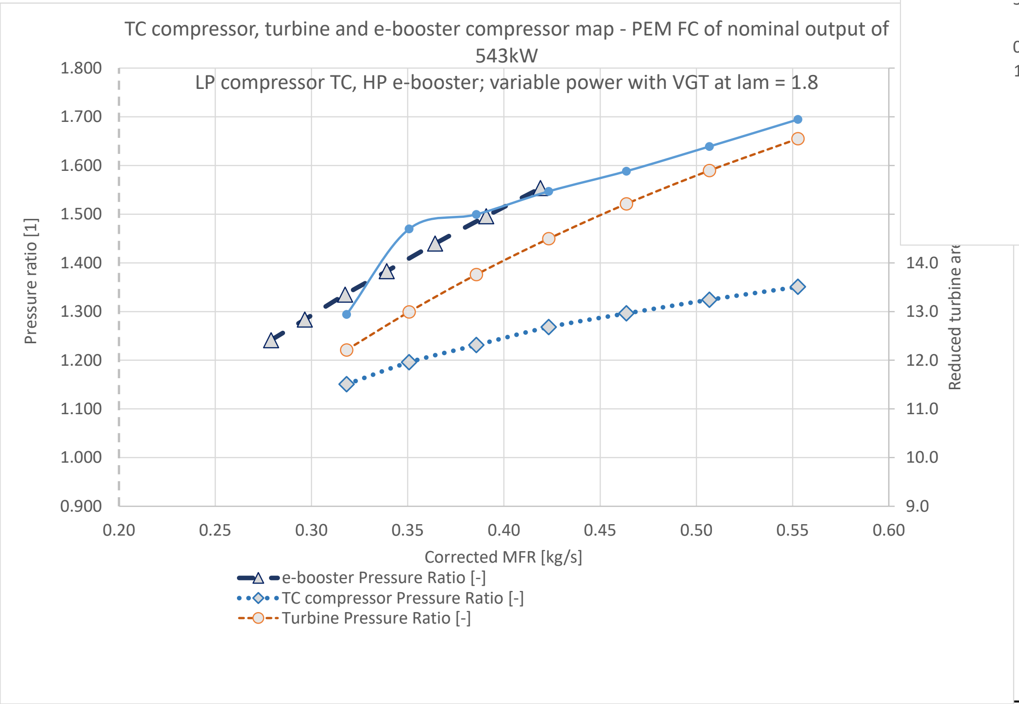


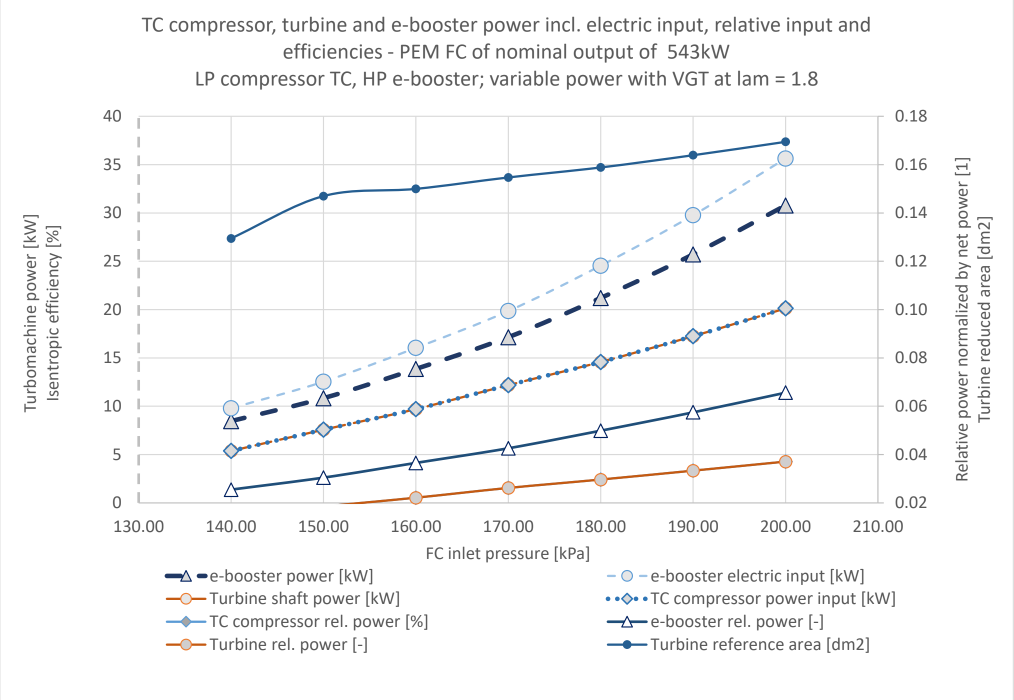
Activities of Work Package 4-WP06 Alternative Fueled Powertrains Future Vehicles: Fuel Cells and Energy Management

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-WP06-005 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

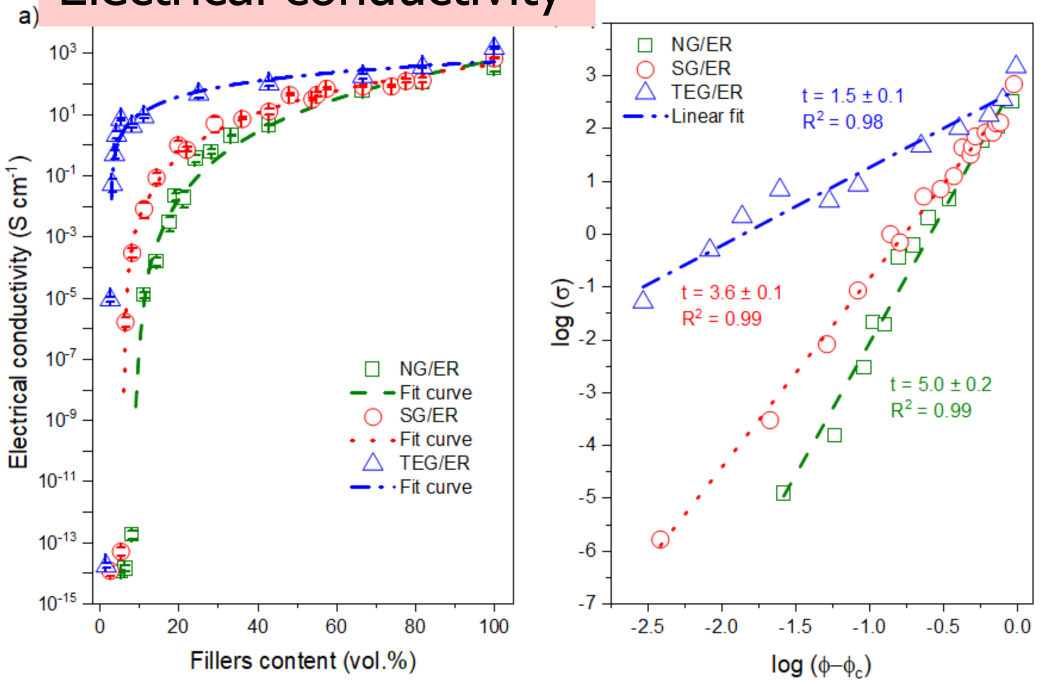
- Stack's BPs

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

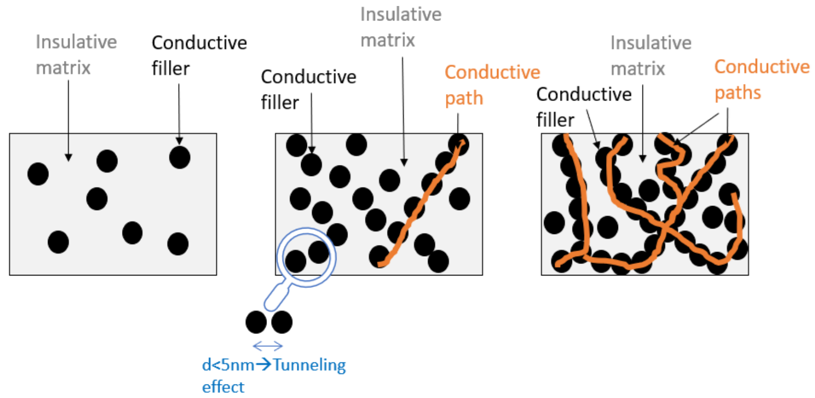
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

Electrical conductivity

Fuel Cell Bipolar Plates Based on Epoxy Resin/Graphite (Austenitická ocel 14 000 S/cm)



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

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

2) Curing conditions: Differential Scanning Calorimetry

DSC thermograms of the epoxy resin system (prepolymer and hardener):

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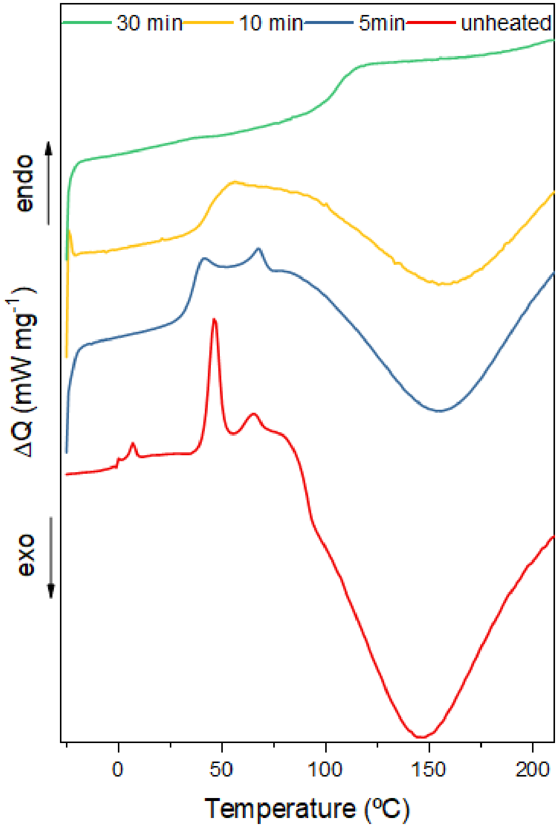
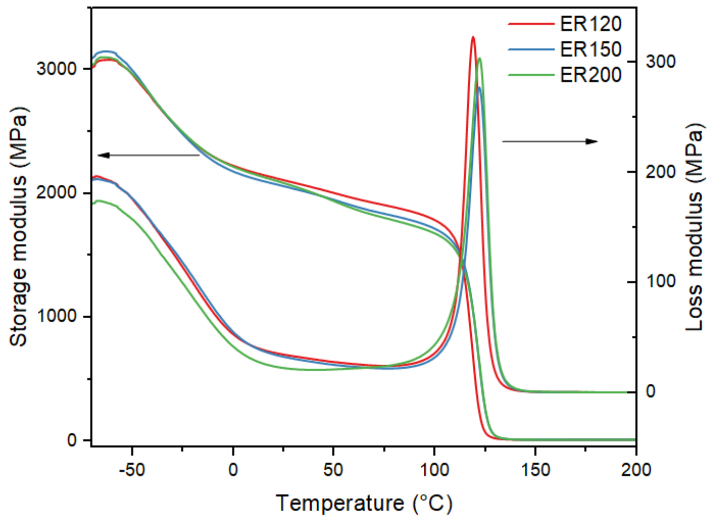


For the processing of the polymer and its composites, the optimal parameters are at temperatures of 120 °C for 40 minutes.

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 *4) Post curing: mechanical properties*



Storage modulus: stored energy during the load phase and proportional to the stiffness of the material

- *The highest storage modulus obtained for the sample post-cured at 120 °C, indicating that the material is rigid and has a high resistance to deformation.*

Loss modulus: dissipated energy during the load phase due to internal friction.

- *The lowest loss modulus observed for epoxy resin post-cured at 150 °C, indicating that the material is elastic and has a high ability to recover the original shape after releasing the force.*

Sample	Description	T_g (ºC)	Storage modulus (E') at 80 °C (MPa)	Loss modulus (E") at 80 °C (MPa)
ER120	Post-cured at 120 ºC for 3h	119	1884	24.5
ER150	Post-cured at 150 ºC for 3h	122	1817	21.6
ER200	Post-cured at 200 ºC for 3h	122	1777	26

Taking into account the mechanical and thermo-mechanical properties of each sample, the best conditions for the post-curing are:
Temperature: 120 ºC
Time: 3 hours.

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

Development of the new electrochemical method for measuring gas permeability of PEM fuel cell components

$H_2 \leftrightarrow 2H^+ + 2e^-$ $\quad E^0 = 0\,V\,vs.SHE$ ⟶ *Overpotential applied = 0.4 V/SHE*

$O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O$ $\quad E^0 = 1.2\,V\,vs.SHE$ ⟶ *Overpotential applied = 0.8 V/SHE*

Electrochemistry basis

Gas molecules	Diameter molecule (nm)
Helium (He)	0.260
Hydrogen (H_2)	0.289
Carbon Dioxide (CO_2)	0.330
Oxygen (O_2)	0.346
Nitrogen (N_2)	0.364
Methane (CH_4)	0.380
Butane (C_4H_{10})	0.500

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

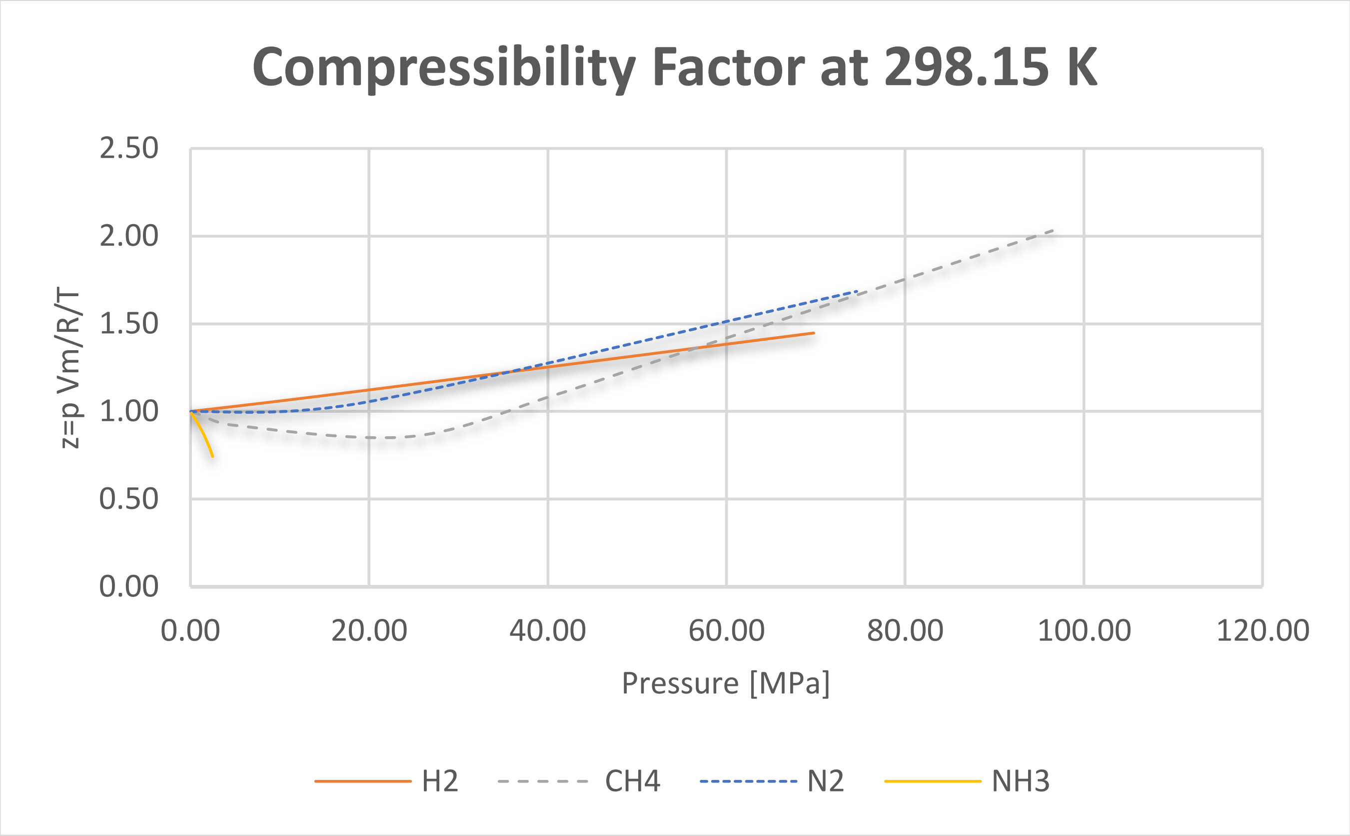
4 *DOE's 2020 technical and cost targets for bipolar plates*

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

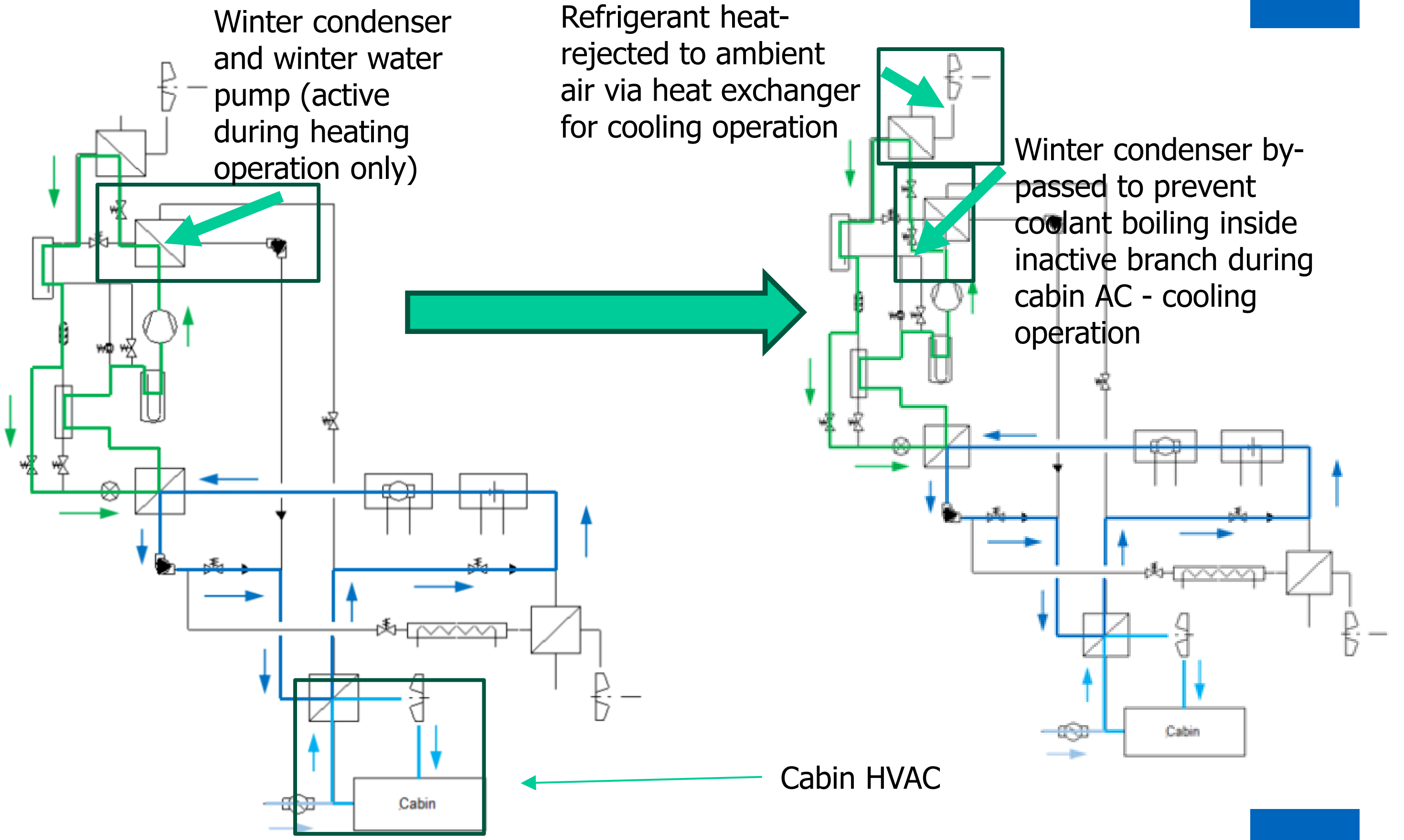
- Simulations of power requirements and pressure cylinder filling process for design of H2 production unit – physical bases for a model
- Programming of real gas features using BWR and Redlich Kwong equations of state BWR_v2.xslx inc. Joule-Thompson coefficient and real work for compression



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

- 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.



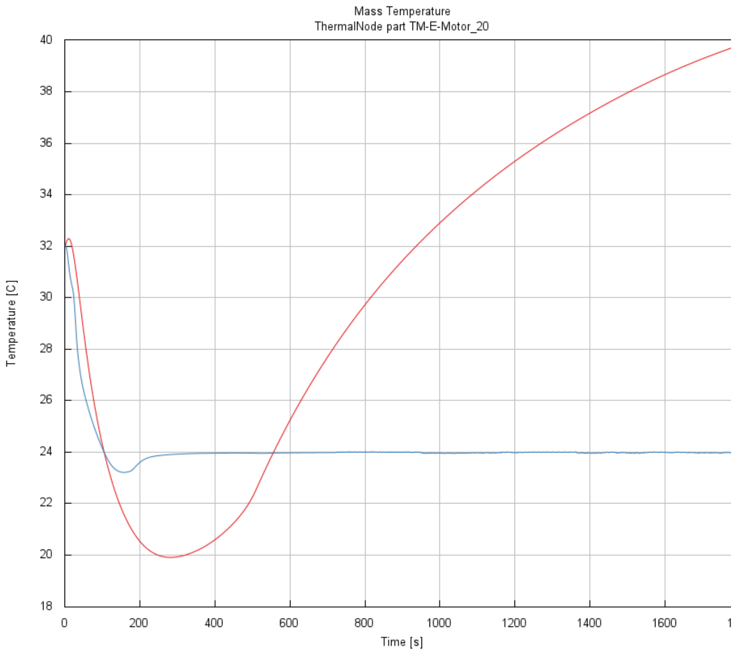
Activities of Work Package 4-WP06 Alternative Fueled Powertrains and Energy Consuming Auxiliaries for Future Vehicles: Fuel Cells and Energy Management

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

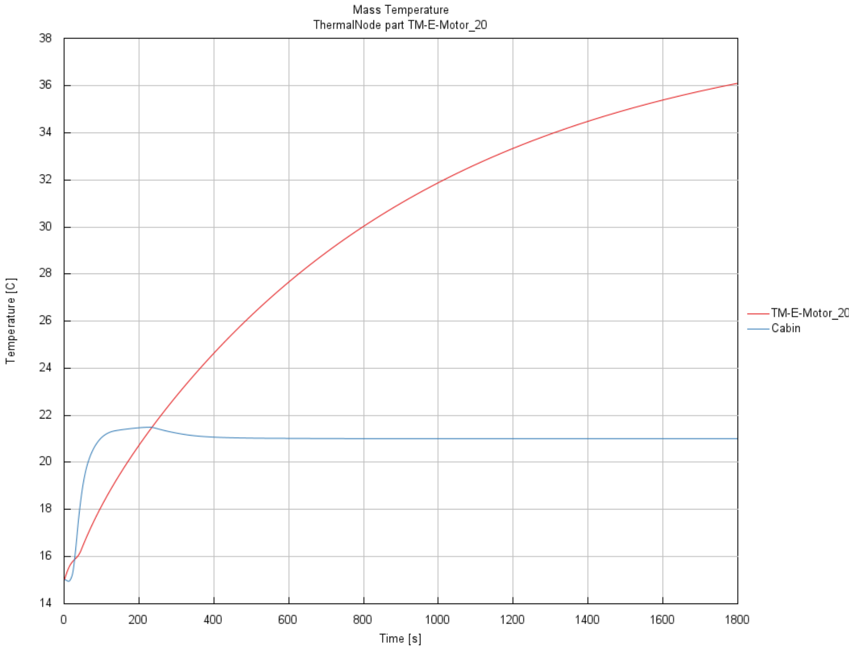
- Operation during cabin and electric powertrain cooling - left. Before change to heating mode is done, the "summer" condenser has to be evacuated.
- Operation during cabin heating, using waste heat from electric powertrain and heat from ambient air - right.
- Thaw temporary mode for ice removal from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