FEV Webinar
Automotive World

Aachen, 8th April 2020

M. Zubel, Electronics and Electrification, Fuel Cell and Fuel Cell Systems
Agenda

- Introduction FEV
- Challenges of Fuel Cell Development
- Fuel Cell Modelling Framework
- Summary
Your engineering and consulting partner –
Strong, competent and reliable

GLOBAL REACH – ONE FACE TO THE CUSTOMER

- 735 M€ Revenue expected in 2019
- ~200 Patent applications per year
- 300+ Test cells for engines, T/M, e-drives, fuel cells & batteries
- >40 Years of experience
- >40 Subsidiaries on five continents
- >70% Academics
- >50 Different nations
- 6,700 Employees globally

~200 Test cells for engines, T/M, e-drives, fuel cells & batteries

>40 Years of experience

>70% Academics

>50 Different nations

6,700 Employees globally
Selected fuel cell reference projects

HyPower Bora

1998

1st Fuel cell control unit

Truck APU

2006

1st FCEV benchmark

Fuel cell range extender

2014

Commercial Vehicle with FC

Fuel cell electric multiple unit

Hyundai Nexo benchmark

2020

OVER 20 YEARS OF EXPERIENCE IN FUEL CELL DEVELOPMENT
Agenda

- Introduction FEV
- Challenges of Fuel Cell Development
- Fuel Cell Modelling Framework
- Summary
The automotive application of fuel cells poses high requirements on flexibility, durability and safety

CHALLENGES AND SOLUTIONS OF FUEL CELL OPERATION

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Solutions</th>
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<tbody>
<tr>
<td>Transient operation</td>
<td>Multi-level modelling</td>
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<td>Status of health &amp; end of life prediction</td>
<td>Multi-level testing From cell to system</td>
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<td>Start-up &amp; stopping procedure</td>
<td>Accelerated stress and endurance testing</td>
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<td>Predictive maintenance</td>
<td>Hybridization</td>
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<td>Cold-start / freeze start procedure</td>
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- **Challenges:**
  - Transient operation
  - Status of health & end of life prediction
  - Start-up & stopping procedure
  - Predictive maintenance
  - Cold-start / freeze start procedure

- **Solutions:**
  - Multi-level modelling
    - Sub-model
    - 1st level
    - 2nd level
    - 3rd level
  - Multi-level testing
    - From cell to system
  - Accelerated stress and endurance testing
  - Hybridization
Frontloading – Use of component simulation results for system simulation and FCCU pre-calibration to reduce testing and calibration effort

V-MODEL FOR FUEL CELL SYSTEM DEVELOPMENT

Multi-Level Modelling

For every single component

Focus on FC system testing

Reduced duration and scope of tests

Reduced calibration effort

FCCU: Fuel Cell Control Unit, BoP: Balance of Plant (auxiliary units)
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Modular modelling framework for fuel cell vehicle development: Overview

**GENERAL SETUP OF THE MODULAR MODELING ENVIRONMENT**

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* Level 3 models sometimes need dedicated software for modelling and are standalone models. They can use interface inputs from Level 1 and Level 2 models.

**PROJECT DEPENDENT**

Modular setup: Universal interfaces  Exchangeability: Different levels of fidelity and complexity  User-specific models

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M. Zubel | Webinar: FC Simulation | 8th April 2020

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Each building block is interchangeable and has different levels of fidelity and complexity

**OVERVIEW SIMULATION LEVELS**

<table>
<thead>
<tr>
<th>LEVEL 1</th>
<th>Concept study and plant model for XiL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Typically necessary for plant model)</td>
<td>0D/1D simulation with simplified models</td>
</tr>
<tr>
<td></td>
<td>Legislation cycles, RDE, performance</td>
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<td></td>
<td>Excel based tool, MATLAB/Simulink</td>
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<table>
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<tr>
<th>LEVEL 2</th>
<th>Detailed system simulation</th>
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<tr>
<td>(Typically necessary for system development)</td>
<td>0D-2D simulation with detailed models</td>
</tr>
<tr>
<td></td>
<td>System layout, sizing of components</td>
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<td></td>
<td>Map-based and physical modelling</td>
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<th>LEVEL 3</th>
<th>Detailed component assessment</th>
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<tr>
<td>(Dedicated software with suitable interfaces to level 1 and 2)</td>
<td>3D multi-physical component modelling</td>
</tr>
<tr>
<td></td>
<td>Interfaces to lower level models</td>
</tr>
<tr>
<td></td>
<td>Optimization of components with dedicated software</td>
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</table>
Fluid flow modeling:
Universal media interfaces and modular structure

CONNECTIONS OF COMPONENTS ARE MODELLED AS DISCRETE VOLUMES AND PRESSURE DROPS

\[
\bar{\phi}_i = \begin{pmatrix} p_i \\ m_i \\ T_i \\ x_i \end{pmatrix}
\]

Universal interface:
\( pTmx \) - vector

Fluid path modelling

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>P</th>
<th>T</th>
<th>( \dot{m} )</th>
<th>x Products / Educts</th>
<th>Contaminants</th>
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</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>Pressure</td>
<td>Temperature</td>
<td>Mass Flow Rate</td>
<td>( \text{H}_2 )</td>
<td>( \text{H}_2\text{O} )</td>
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Source: VKA

M. Zubel | Webinar: FC Simulation | 8th April 2020
Modular modelling framework for fuel cell vehicle development: Stack modelling

**GENERAL SETUP OF THE MODULAR MODELING ENVIRONMENT**

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Modular setup: Universal interfaces  Exchangeability: Different levels of fidelity and complexity  User-specific models

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Pseudo 2D Simulink cell model:
More accurate representation of species and humidity distribution

SINGLE CELL IS SEGMENTED TO ENABLE PSEUDO 2D REPRESENTATION

- Gas channel is divided into one to five sections
- Segmentation reflects influence of concentration changes

Source: ZBT, VKA
Stack model is based on single cell model and extended by models describing thermal behavior and membrane humidity

- Simulation of the two most important cells
  - one representative center cell
  - one border cell
- The fluids are split into the (# cells - 2) center cells and 2 border cells
- The 2D single cell model is extended by
  - a thermal model
  - a dynamic model to describe membrane humidity
- \( N_2 \) diffusion is integrated

Source: VKA, ZBT
Modular modelling framework for fuel cell vehicle development: Component modelling

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# PROJECT DEPENDENT

Modular setup: Universal interfaces  Exchangeability: Different levels of fidelity and complexity  User-specific models

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Modelling example:
Hydrogen recirculation pump

SIMULATION CHALLENGE

- Transient simulation
- Simulation of multiple pump revolutions
- Presence of small gaps
- Detailed knowledge of gap width required to correctly model internal leakage
- Interaction of two lobes
- High number of cells necessary, especially for large pumps

→ High computational effort for 3D CFD
Modelling example:
Reduction of computational effort possible via reduction to 2D

THEORY OF SIMILARITY APPLIES TO POSITIVE DISPLACEMENT PUMPS

2D Reduction

- Reduced computational effort
  \[ \frac{n_{\text{Cell,3D}}}{n_{\text{Cell,2D}}} = \frac{z_{\text{max}}}{\Delta x_{\text{cell}}} \]
- Simplification of model

Source: GrabCAD
Modelling example:
Modelling of lobe motion via overset mesh approach

ONLY PART OF THE MESH IS UPDATED EACH TIME STEP

Background mesh (housing) + Overset meshes (lobes) = Overlay

Hole cutting algorithm
Modelling example:
Details of simulation mesh and handling of small gaps

CORRECT GAP WIDTH IS CRUCIAL FOR ACCURATE MODELLING OF INTERNAL LEAKAGE

- Gap width: 75 µm
- With prism layer shrinkage
- Zero gap interface
- With prism layer shrinkage
WELL VALIDATED RESULTS ARE ACHIEVED

- Boundary conditions:
  - Stagnation pressure at inlet
  - Pressure at outlet
  - Pump speed

- Only small deviations between simulation and experiment

- Sufficient results achieved by simulating only two pump revolutions

- Linear performance characteristic of positive displacement pump
Modelling example:  
Instantaneous flow rate

FLOW RATE HAS TO BE AVERAGED FOR COMPARISON TO EXPERIMENTAL DATA

Description
- Calculation of average flow rate:
  \[ \overline{V} = \frac{\int_{0.25n}^{i} \dot{V}(t) \, dt}{(i-0.25)n} \]
  - \( i \): number of pump revolutions
  - \( n \): time per pump revolution
- First quarter revolution is settling time
- Periodical instantaneous flow rate behavior achieved. Differences are due changing time step
Modular modelling framework for fuel cell vehicle development: Vehicle modelling

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Modular setup: Universal interfaces  
Exchangeability: Different levels of fidelity and complexity  
User-specific models

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Validation example: BREEZE!
Fuel cell range extender for battery electric vehicles

Highlights
- Next generation range extender
  - Low temperature polymer electrolyte membrane fuel cell with 30 kW electric power
  - All electric range approx. 300 km
- Identical package as internal combustion engine range extender
  - Metallic bipolar plates
  - Integration of balance-of-plant components
  - Dry cathode/passive humidification at anode

Project consortium

Bipolar Plate (BPP)

Range extender module (REM)

Funders:

Range extender module (REM)
Modelled flow paths are validated with measurement data from BREEZE! project

VALIDATION EXAMPLES: AIR TEMPERATURE AND PRESSURE

Summary
- Throttle position is set as measured
- Deviations in transient operating states can be explained with different controller parameters in simulation and measurement
- Validation is based on limited measurement data from vehicle tests

Source: VKA

M. Zubel | Webinar: FC Simulation | 8th April 2020
Modelled flow paths are validated with measurement data from BREEZE! project

VALIDATION EXAMPLES: WARM UP CURVE, COOLANT TEMPERATURE SPREAD AND THERMOSTAT VALVE POSITION

Source: VKA
Modular modelling framework for fuel cell vehicle development: XiL-Framework

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Model complexity → Computation effort

- Level 1: Coast down parameter based
- Level 2: Mean value; Advanced thermal system
- Level 3: Electro-chemical model / ageing; CFD; Detailed electro-chemical model

Modular setup: Universal interfaces ➔ Exchangeability: Different levels of fidelity and complexity ➔ User-specific models

* Level 3 models sometimes need dedicated software for modelling and are standalone models. They can use interface inputs from Level 1 and Level 2 models.
Modular modelling framework for fuel cell vehicle development: XiL-Framework

UTILIZATION OF FEV'S XMOD SOFTWARE SUITE TO ACCELERATE THE DEVELOPMENT PROCESS

Virtual
- Sub-model
- Vehicle
- Electric motor

Level 1
Typically necessary for high fidelity model
- Coast down parameter based
- Map based

Level 2
Typically necessary for system development
- Advanced thermal system

Level 3
- ... ...

Fuel cell system in test cell
- Fuel cell stack/cell
- BoP components
- Fuel cell thermal management

Virtual
- Battery
- Power electronics

Computation effort
- Map based + single mass thermal model
- Efficiency
- Advanced thermal model
- Detailed electro-chemical model
- CFD
- CFD
- ... ...

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Modular modelling framework for fuel cell vehicle development: XiL-Framework

UTILIZATION OF FEV'S XMOD SOFTWARE SUITE TO ACCELERATE THE DEVELOPMENT PROCESS

xMOD

Fuel cell system in test cell

xMOD

# PROJECT DEPENDENT
xMOD – Co-Simulation and virtual experimentation platform

MULTI-MODEL INTEGRATION & VIRTUAL EXPERIMENTATION

MiL Co-Simulation  SiL Co-Simulation  HiL

» Make your models work together
  xMOD™ provides a heterogeneous model integration environment for models built by different persons using different languages and tools and working within different entities.

» Virtual experimentation lab
  xMOD™ is a simulation platform that adapts its interface to each engineering field: to be an expert in modeling is no longer necessary to run simulations!

» Extreme performance
  Inside of xMOD™ you find highly optimized algorithms and advanced synchronization techniques based on Multi-threading and Multi-core processing

» Ensure continuity from MiL to HiL
  For each ECU development stage, xMOD™ HiL solution will help will help along the wholeV cycle
Agenda

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FLEXIBLE MODELLING FRAMEWORK ENABLES TIME AND COST REDUCTION

- Reduction of development time
- Reduced time to market
- Lower development cost
- Design changes are less costly
- CAE enables frontloading of knowledge
- Efficient modelling framework is required