Solid Oxide Fuel Cell (SOFC) Thermal Management at Cell and System Scales

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Presentation Outline

- **A Pseudo 3D model for planar SOFC integrated with a heating furnace**
- **Temperature profiles in structural layers;**
- **System level modelling and simulation;**
- **Balance-of-Plant analysis**

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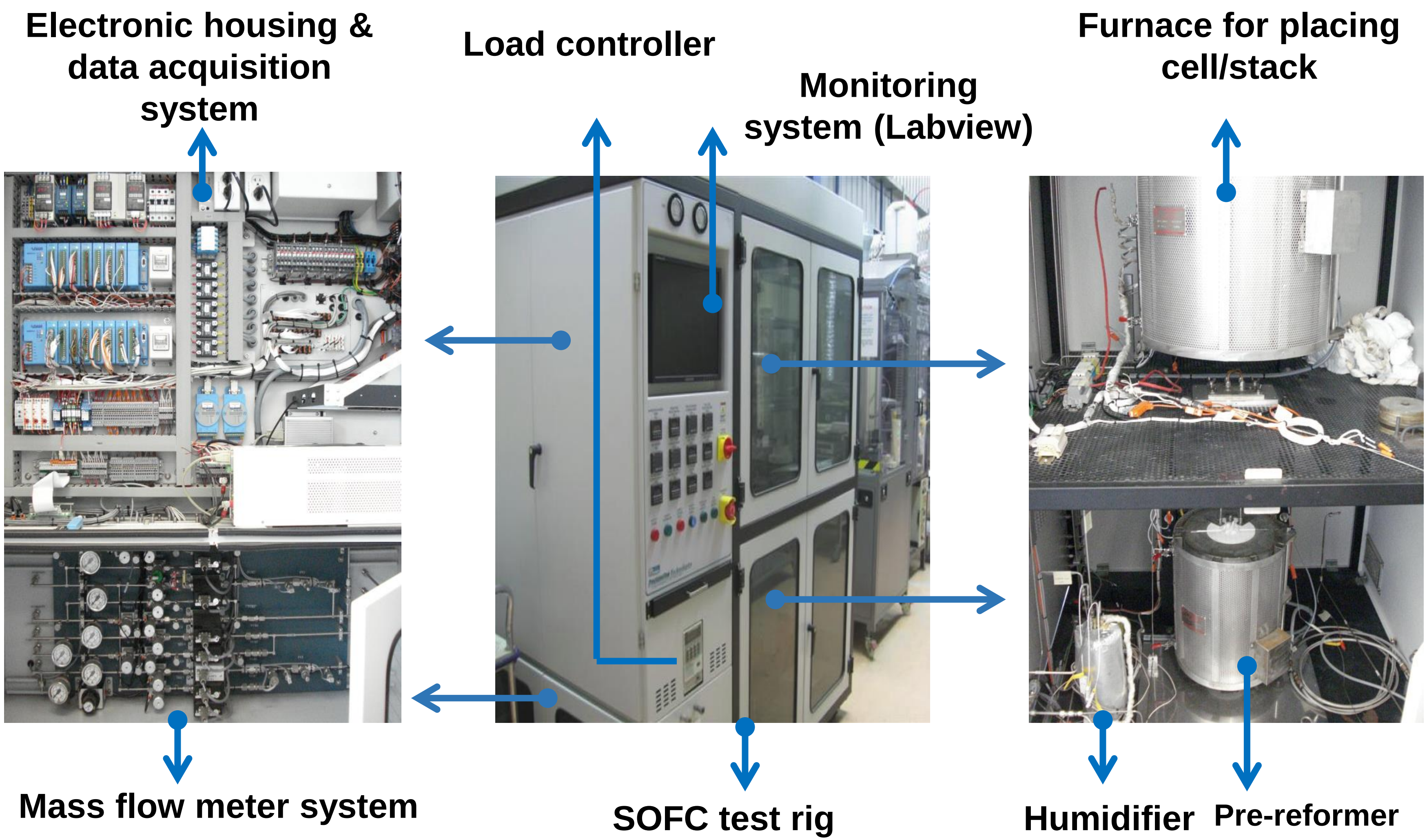
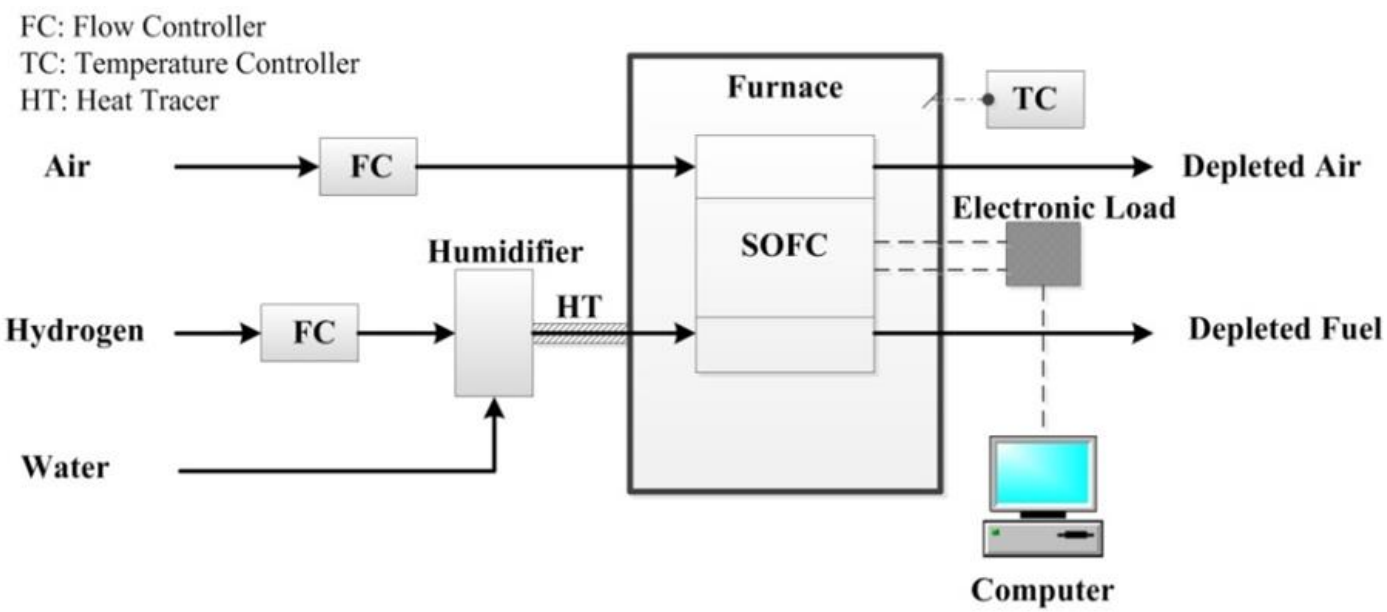
The SOFC test station at Curtin University in collaboration with Ceramic Fuel Cells Ltd.



Test Rig Modelling

A Pseudo 3D Model for Planar SOFC Integrated with a Heating Furnace



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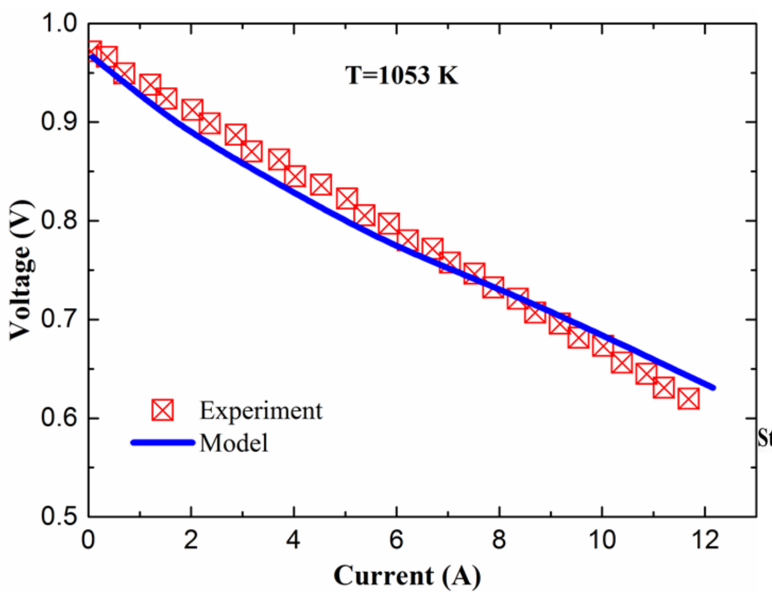
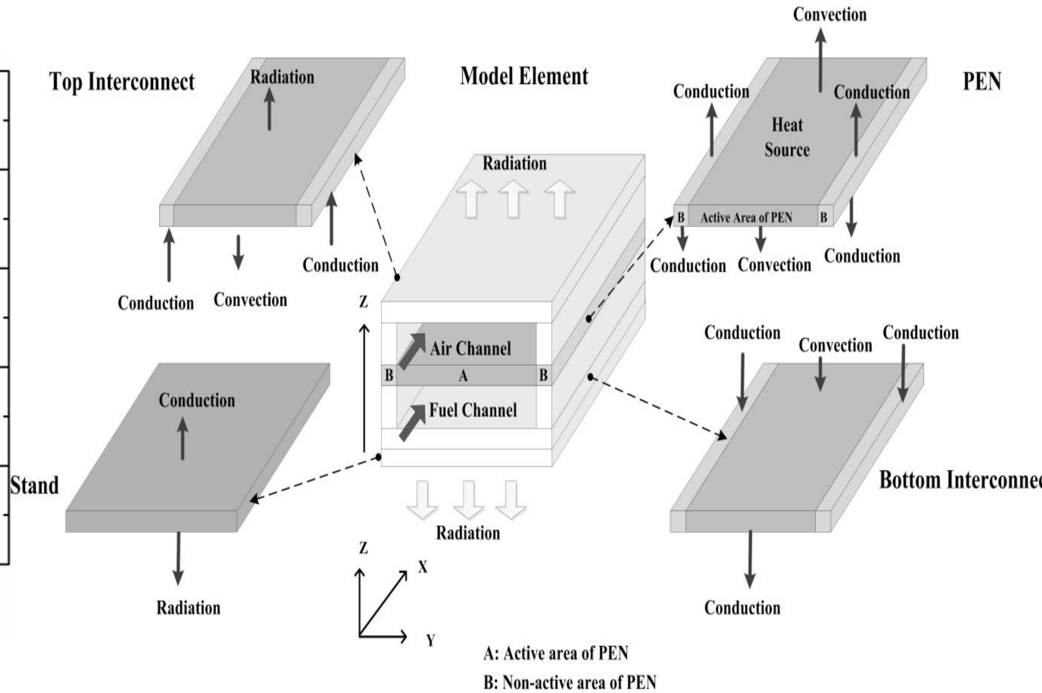
Multi-Layer modelling structure and validation





Four-layer modelling framework including stand, two interconnects, and PEN

Model Capabilities

- Detailed prediction of cell performance and thermal behaviour under both adiabatic and non-adiabatic conditions;
- Adiabatic condition is mostly consistent with cell’s operation in stack (the marketable/commercial scale);
- Non-adiabatic condition is mostly consistent with cell’s operation integrated with a furnace (laboratory scale);
- Detailed insights for temperature profiles in cells structure provides a design and thermal management tool;
- Model-based design of new tests is feasible

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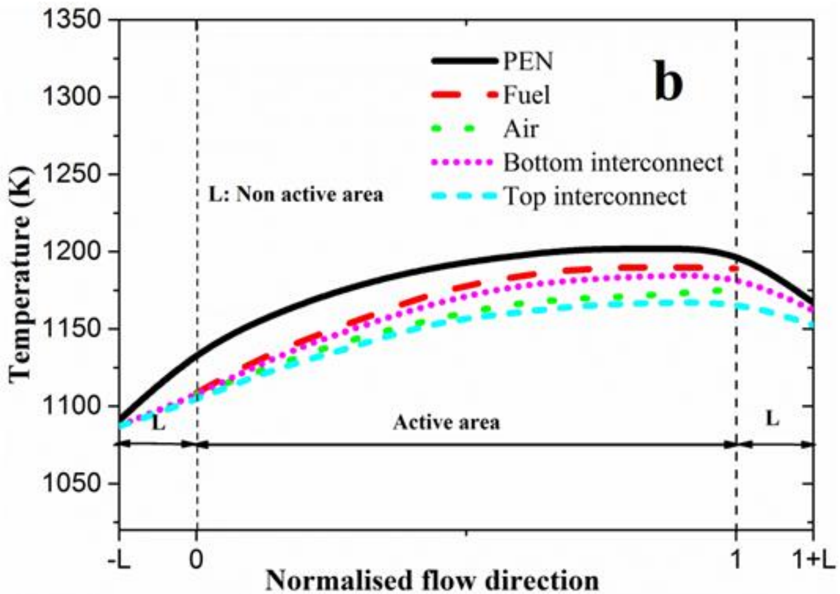
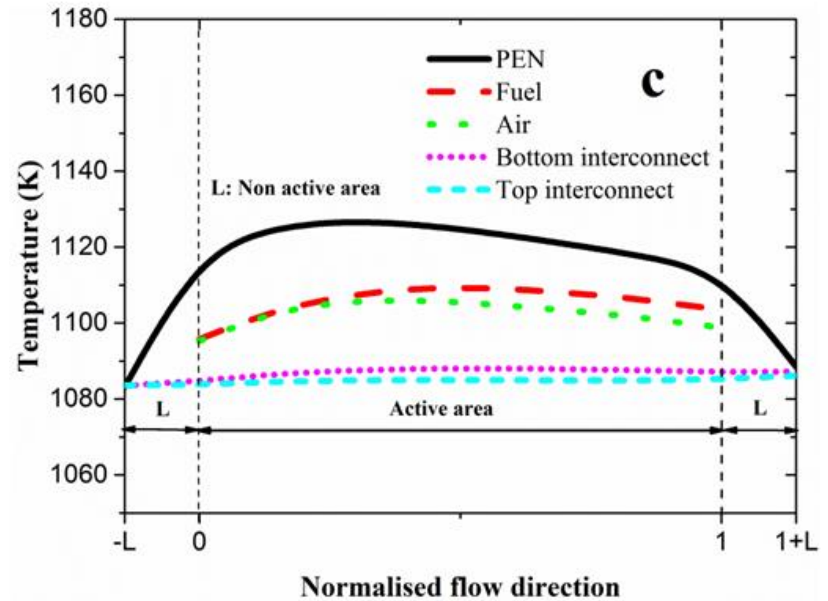
Temperature profiles in structural layers: adiabatic (left) and non-adiabatic(right)





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System level modelling and simulation

Few Challenges and Opportunities:

→A black box/lump module is numerically efficient;
BUT misses the main features of SOFC

→A distributed module accounts for detailed transport and reaction kinetics;
BUT causes serious complexity

→More dimensions → more analysis feasible;
BUT more numerical facilities and proficiency needed

→A flowsheeting package is not a suitable tool for discretization purposes due to meshing difficulties;
BUT offers thermodynamics data bases and process analysis and optimization tools;

***Solution**:* Compromise

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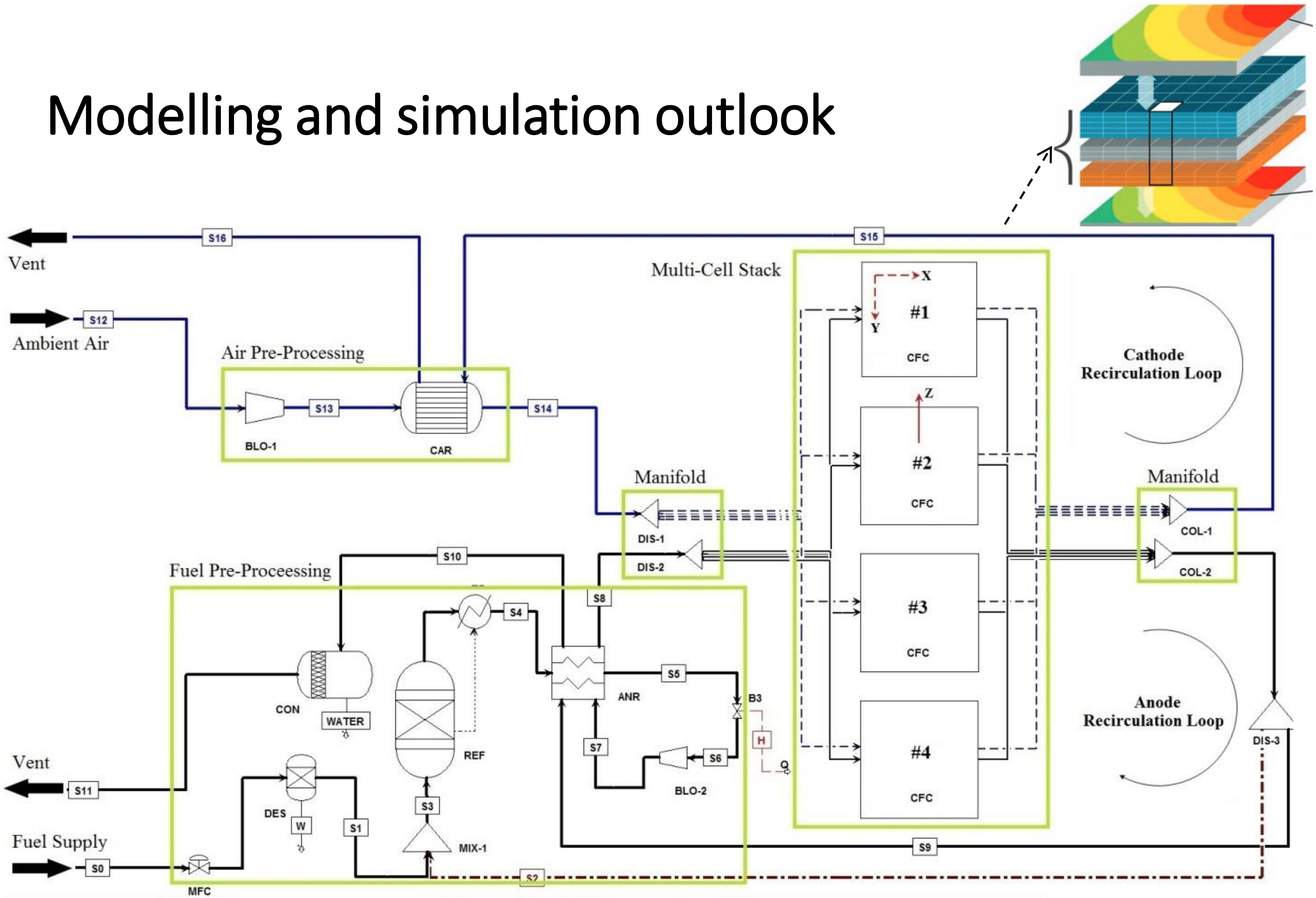
Modelling and simulation outlook



ANR: Anode Recuperator
BLO: Blower
CAR: Cathode Recuperator
COL: Collector
CON: Condenser
DES: Desulpuriser
DIS: Distributor
MFC: Mass Flow Controller
REF: Reformer
MIX: Mixer
CFC: Co-Flow Cell

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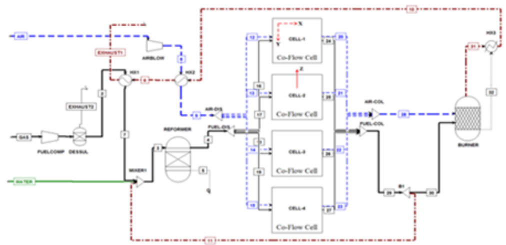
Modelling Platform



System Scale (1 m – 10 m)

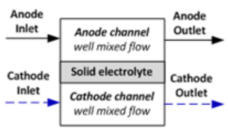
Typical Issues

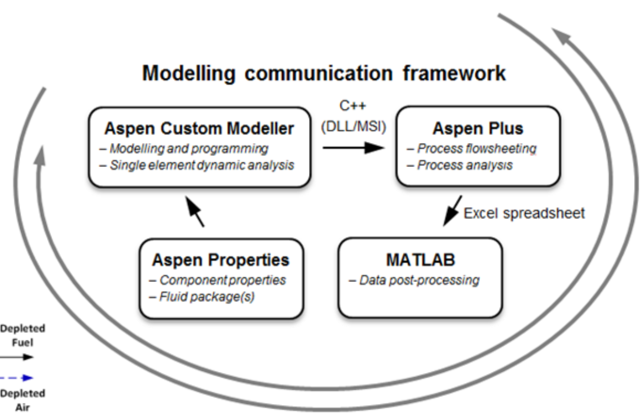
- Process optimisation
- Process dynamics and control
- Process commercialisation

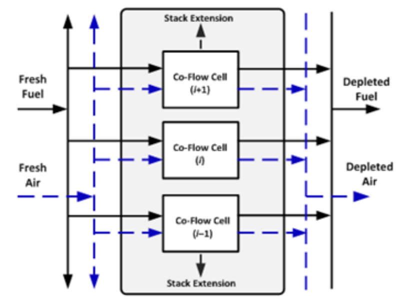
Compartment Scale (1 μm – 1 cm)

Typical Issues

- Reaction kinetics, heat and mass transfer
- Fuel conversion, carbon deposition
- Catalyst and material improvements







Stack Scale (10 cm – 1 m)

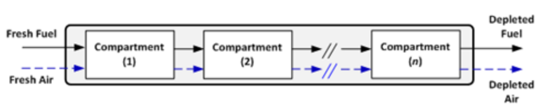
Typical Issues

- Stack energy integration
- Process steadiness
- Start-up and shut-down dynamics

Channel Scale (1 cm – 10 cm)

Typical Issues

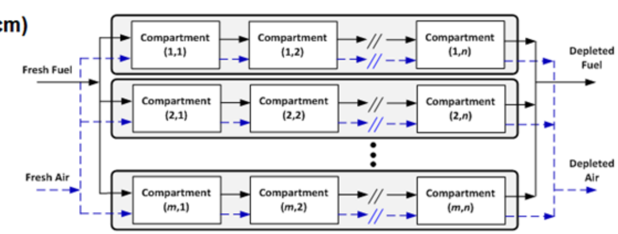
- Fuel and air flow configuration
- Fluid flow regimes
- Residence time distributions



Cell Scale (1 cm – 10 cm)

Typical Issues

- Thermal management
- Cell life durability
- Dynamic cell behaviour



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Model capabilities

- Prediction of SOFC performance at different scales and with adjustable details(0-3D);
- System level modelling, flowsheeting, analysis, and design;
- Optimization capability through both operating variable manipulation and process flow diagram improvement;
- Potential room for dynamic and control research at system level;
- Utilization of well-stablished components data bases and thermodynamical packages;
- Establishment of a modular modelling library customised for electrochemical reactors such as SOFC, MCFC, ...
- Fuel processing analysis without further programming/modelling needs;

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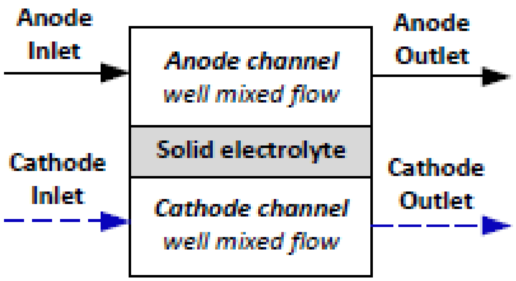
Compartment Scale Assembly capable for 0D modelling of the SOFC

Compartment Scale (1 μm – 1 cm)

Typical Issues

- Reaction kinetics, heat and mass transfer
- Fuel conversion, carbon deposition
- Catalyst and material improvements



Recommended for flowsheeting purposes and dynamic studies

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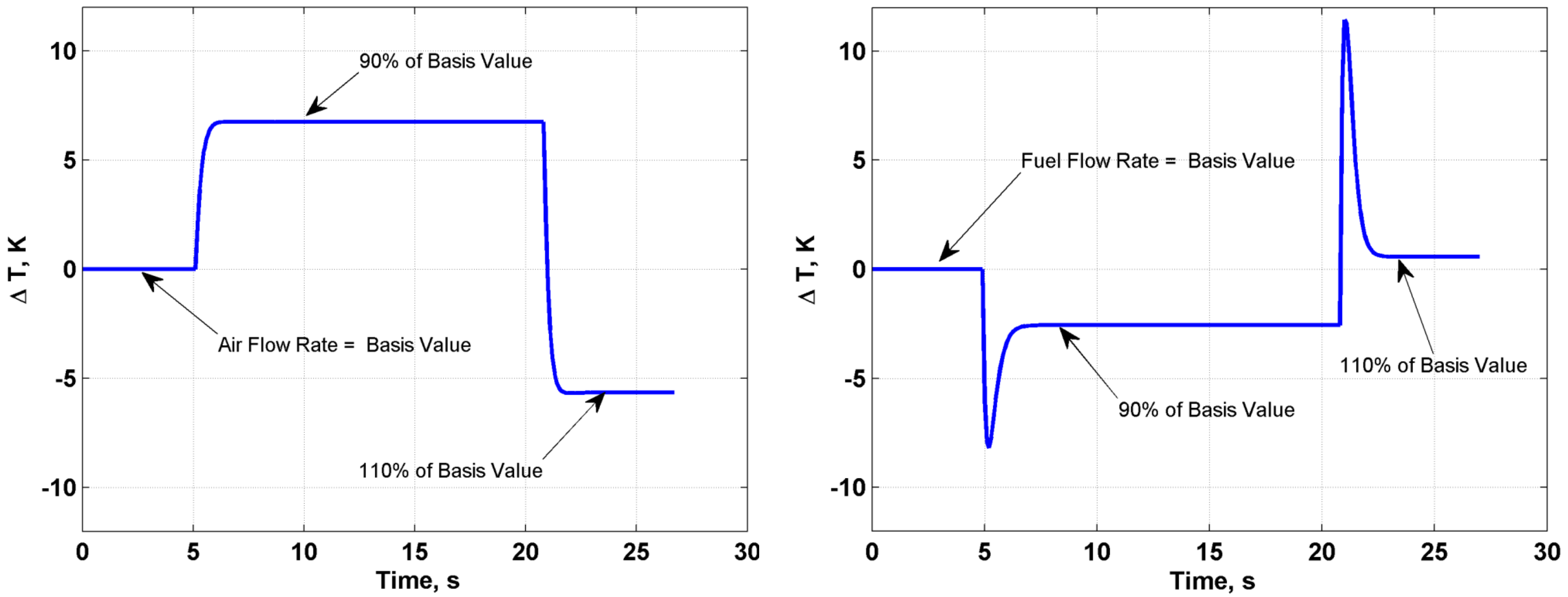
Dynamic sensitivity analysis at compartment scale: temperature response to the air and fuel perturbation



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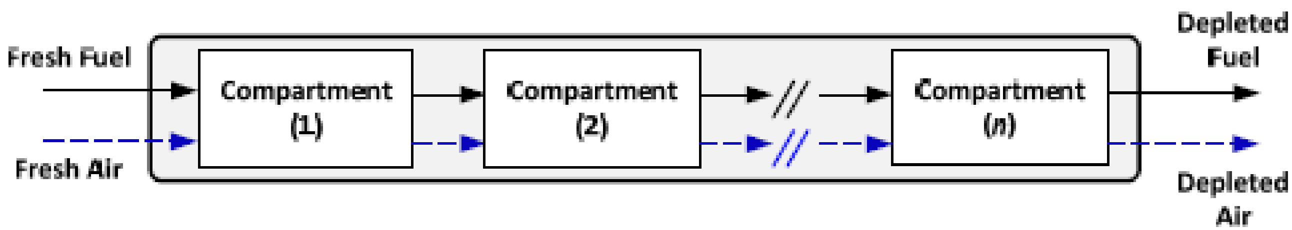
Chanel Scale Assembly capable for 1D modelling of the SOFC

Channel Scale (1 cm – 10 cm)

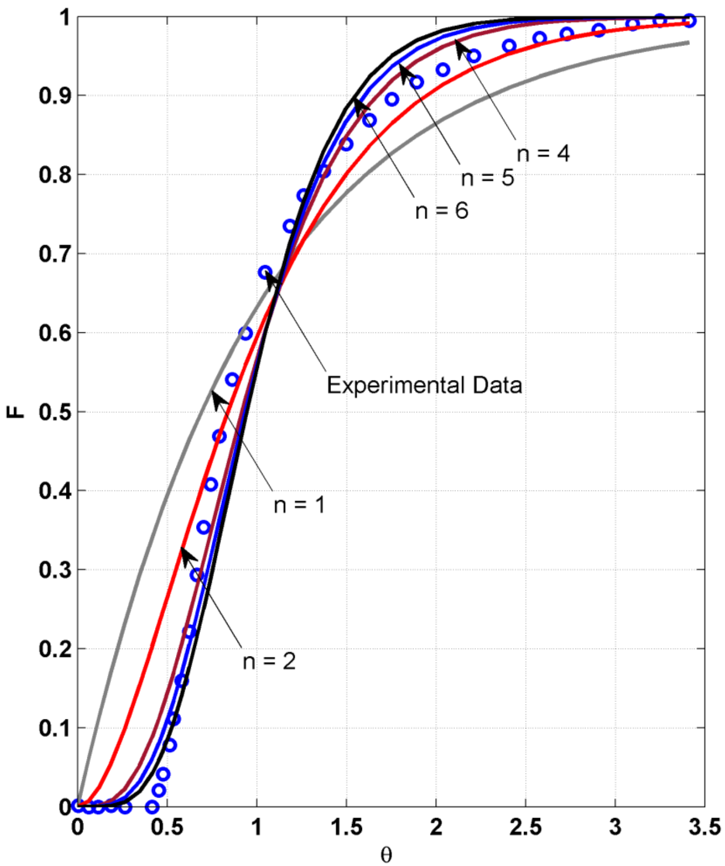
Typical Issues

- Fuel and air flow configuration
- Fluid flow regimes
- Residence time distributions



Recommended for Co-flow and Counter flow SOFC modelling as well as flowsheeting purposes

Estimation of number of compartments in series based on reactor's Residence Time Distribution



Circles:

Experimental RTD data (Krewer et al. (2004))

Solid lines:

Prediction based on n compartments

$$F = 1 - e^{-n\theta} \sum_{i=1}^{n} \frac{(n\theta)^{i-1}}{(i-1)!}$$

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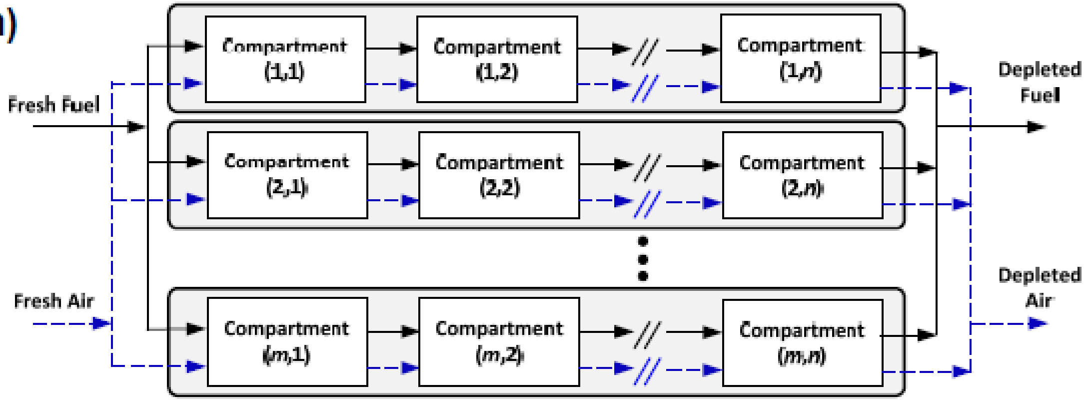
Cell scale assembly capable for 2D modelling of the SOFC

Cell Scale (1 cm – 10 cm)

Typical Issues

- Thermal management
- Cell life durability
- Dynamic cell behaviour



Recommended for SOFC modelling at lab scale and flowsheeting purposes

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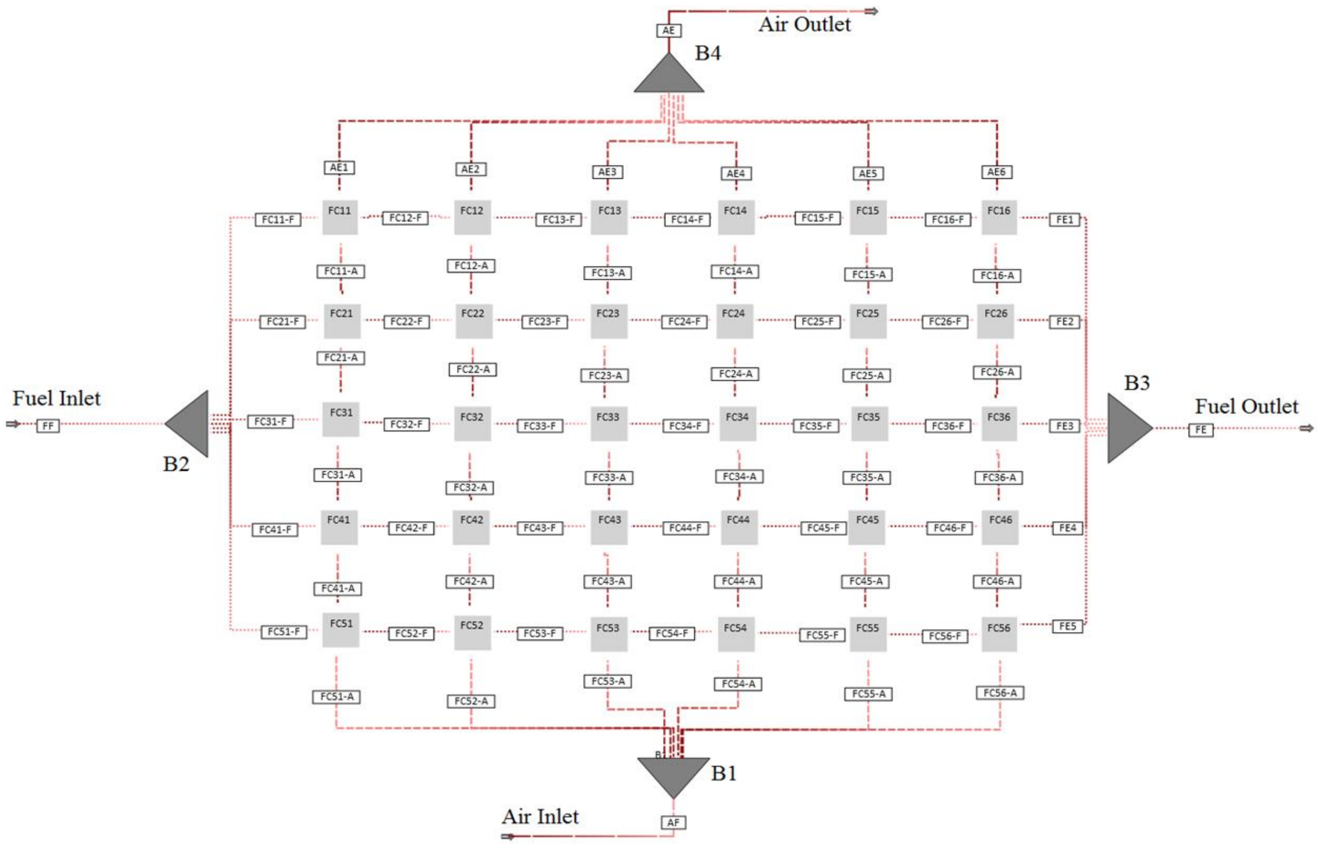
Distributed Cell embedded in a Balance of Plant (Aspen Plus implementation)



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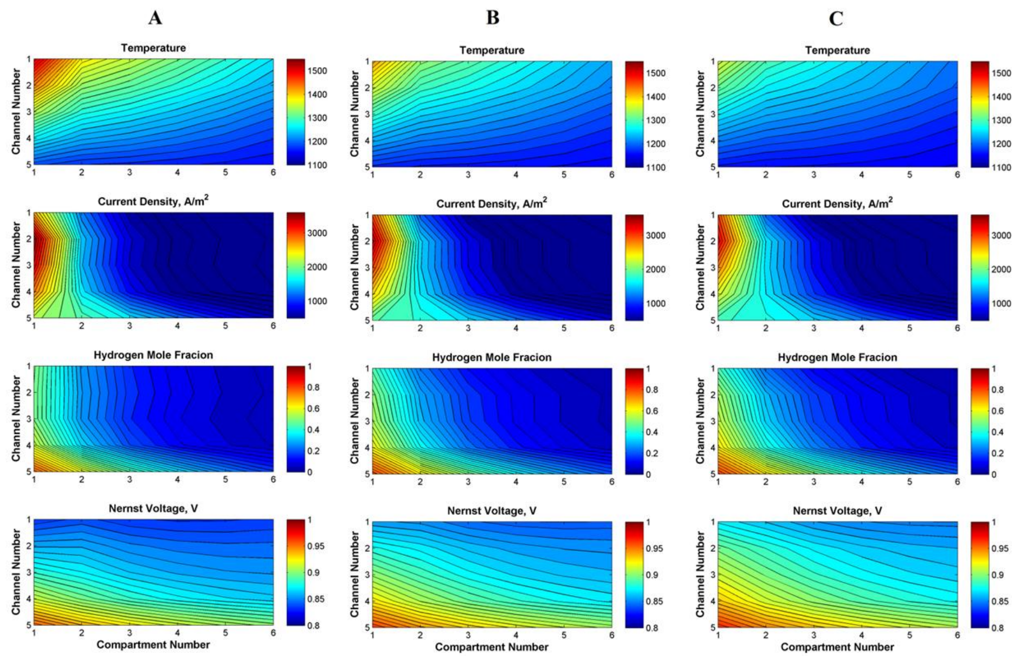
Sensitivity Analysis at Cell Scale: Air Flow Rate Impact



Higher air flow rate results in

- more homogeneity in cell's distributed variables
- Lower average temperature and supressing the electrochemical reaction/current generation;
- Higher pressure drop/costs

Variable	A (Air flow rate 20% lower than base case)	B (Base case air flow rate)	C (Air flow rate 20% higher than base case)
Average Temperature, K	1265	1235	1215
Temperature Coefficient of Variation	0.0663	0.0522	0.0432
Average Current Density, A/m^2	1113	1108	1099
Current Density Coefficient of Variation	0.8854	0.8482	0.8119
Average Nernst Voltage, V	0.873	0.883	0.891
Average Hydrogen Mole Fraction	0.25	0.26	0.27
Fuel Utilization	0.91	0.90	0.89

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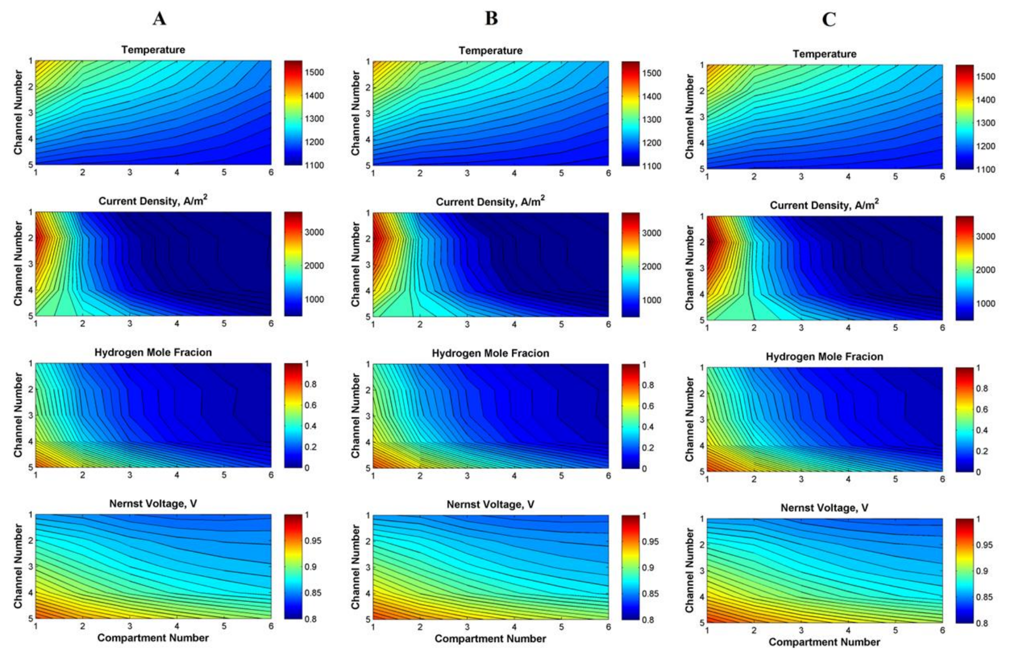
Sensitivity Analysis at Cell Scale: Fuel Flow Rate Impact

Higher fuel flow rate results in

- less homogeneity in cell's distributed temperature
- Higher average temperature and improved electrochemical reaction/current generation;
- Less fuel utilization

All due to more reactant availability in all parts of the cell



Variable	A (Fuel flow rate 10% lower than base case)	B (Base case fuel flow rate)	C (Fuel flow rate 10% higher than base case)
Average Temperature, K	1229	1235	1239
Temperature Coefficient of Variation	0.0517	0.0522	0.0532
Average Current Density, A/m^2	1012	1108	1195
Current Density Coefficient of Variation	0.9056	0.8482	0.8199
Average Nernst Voltage, V	0.881	0.883	0.885
Average Hydrogen Mole Fraction	0.24	0.26	0.28
Fuel Utilization	0.92	0.90	0.88

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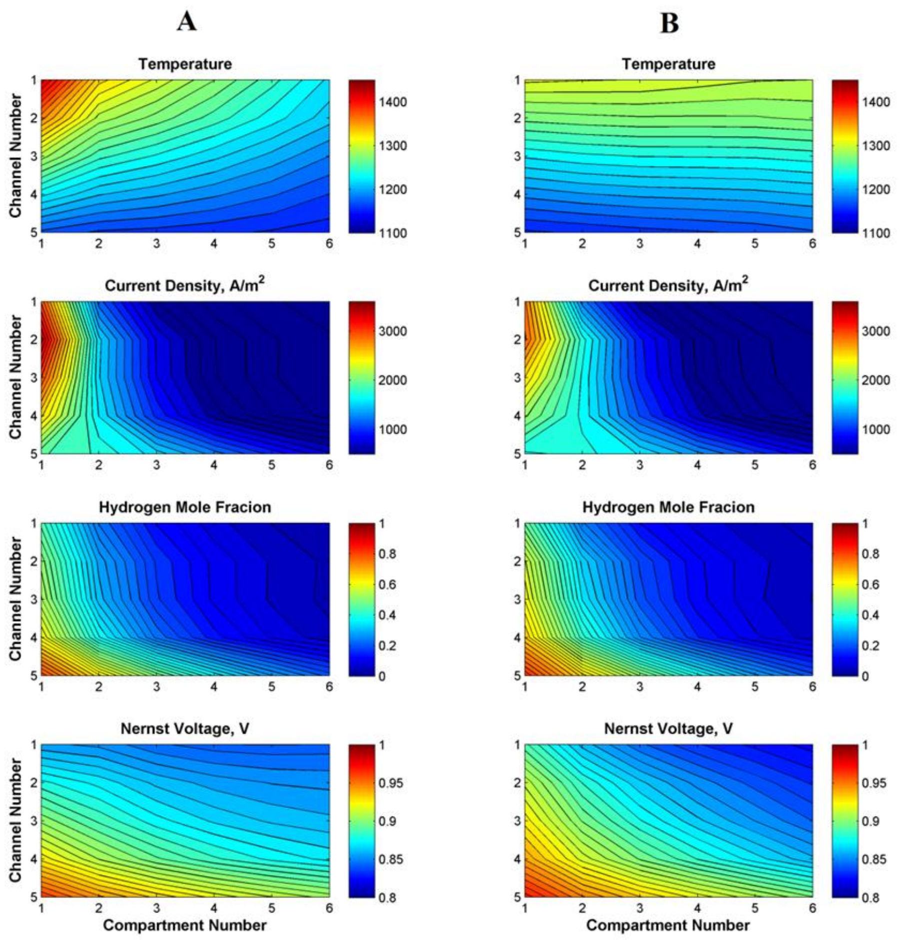
Optimization at Cell Scale: Air Distribution

Optimized Air distribution (B) shows:

- more homogeneity in cell's distributed variables for both temperature and current (desired) ;
- Hot spot is removed (desired). ;
- Not significant change in generated current and fuel utilization (desired).

Variable	Non-Optimised	Optimised
Average Temperature, K	1235	1238
Temperature Coefficient of Variation	0.0522	0.0407
Average Current Density, A/m^2	1108	1098
Current Density Coefficient of Variation	0.8482	0.7554
Average Nernst Voltage, V	0.883	0.884
Average Hydrogen Mole Fraction	0.26	0.28
Fuel Utilization	0.90	0.89



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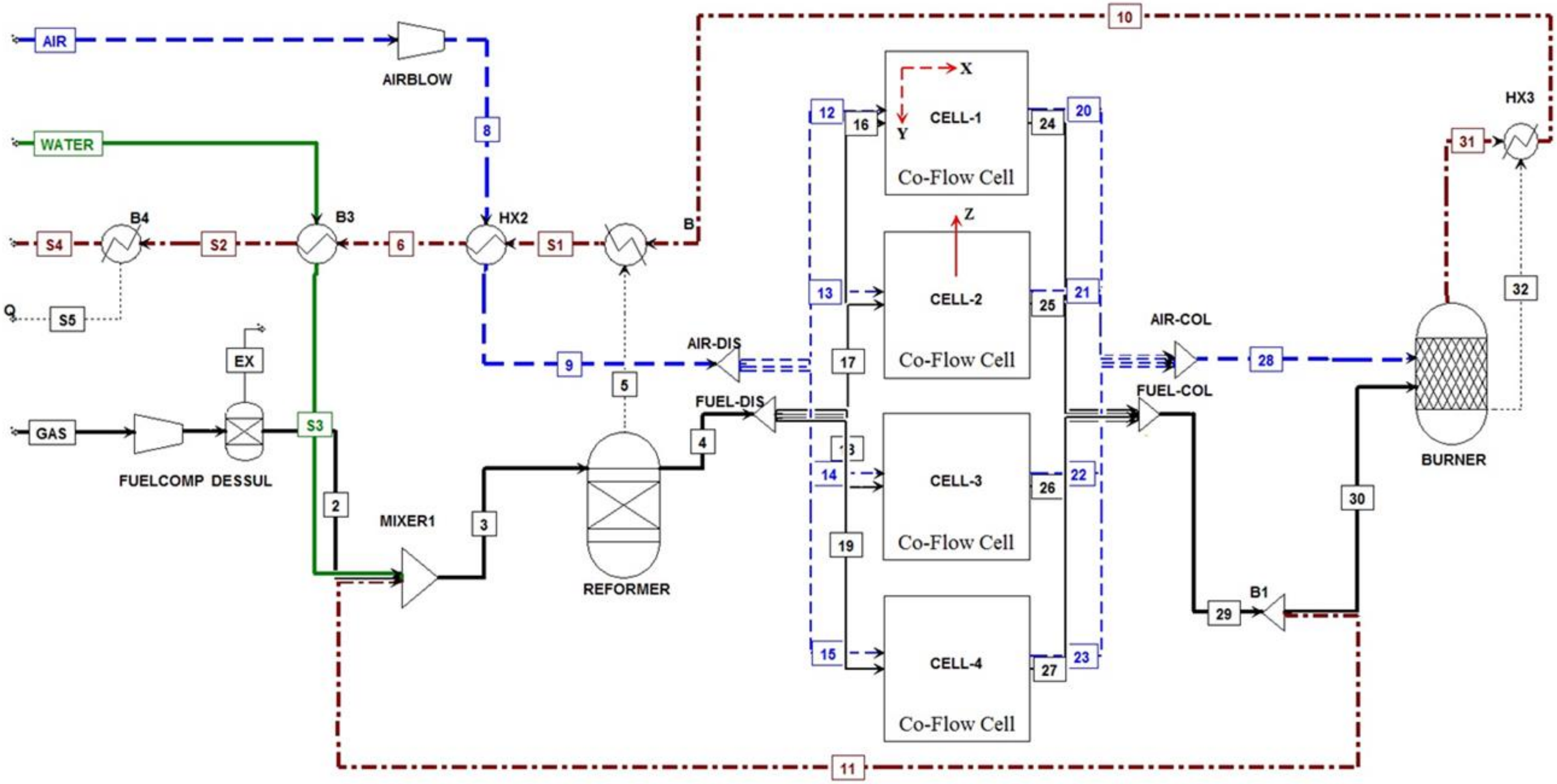
System scale assembly

Simulated plant with external Methane reforming process



Recommended for Balance of Plant modelling and flowsheeting purposes

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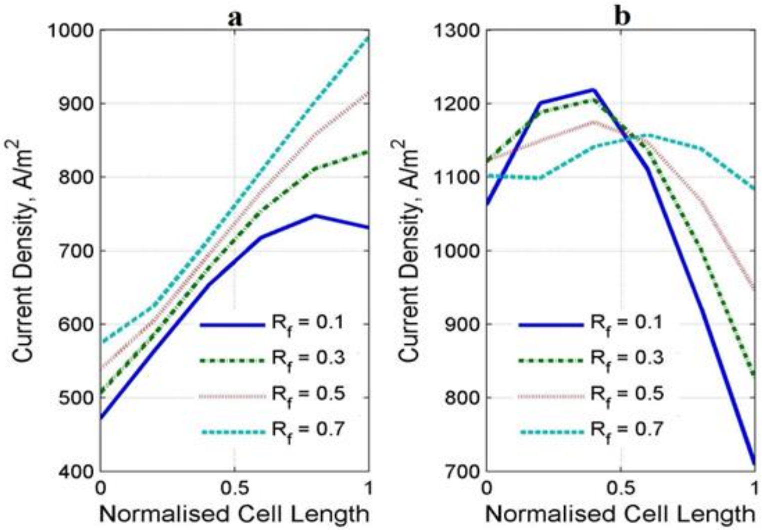
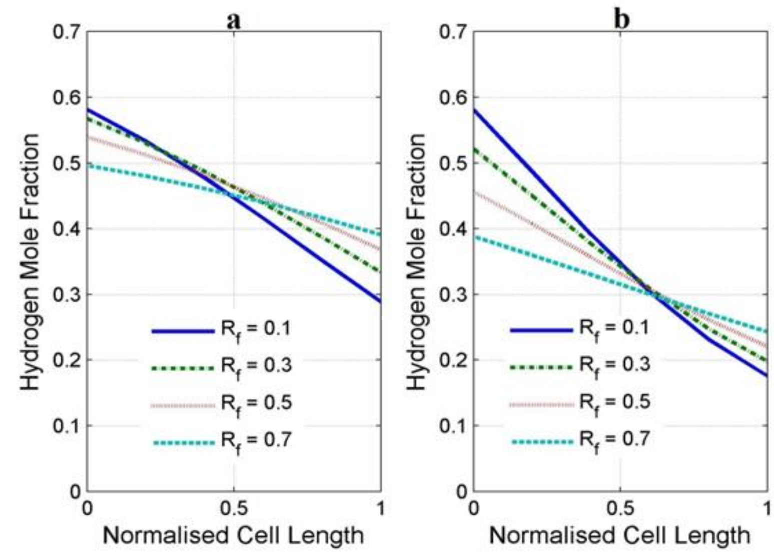
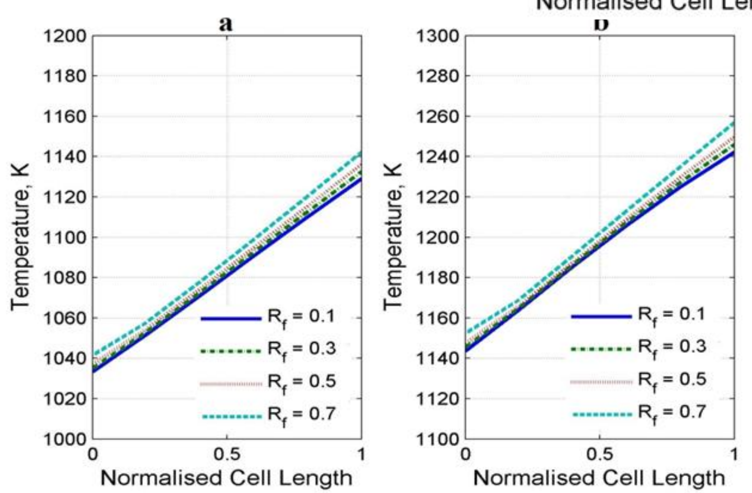
Balance of Plant Analysis

Distributed variables affected by reformer temperature: (a) Reformer T = 973 K; (b) Reformer T = 1073 K.







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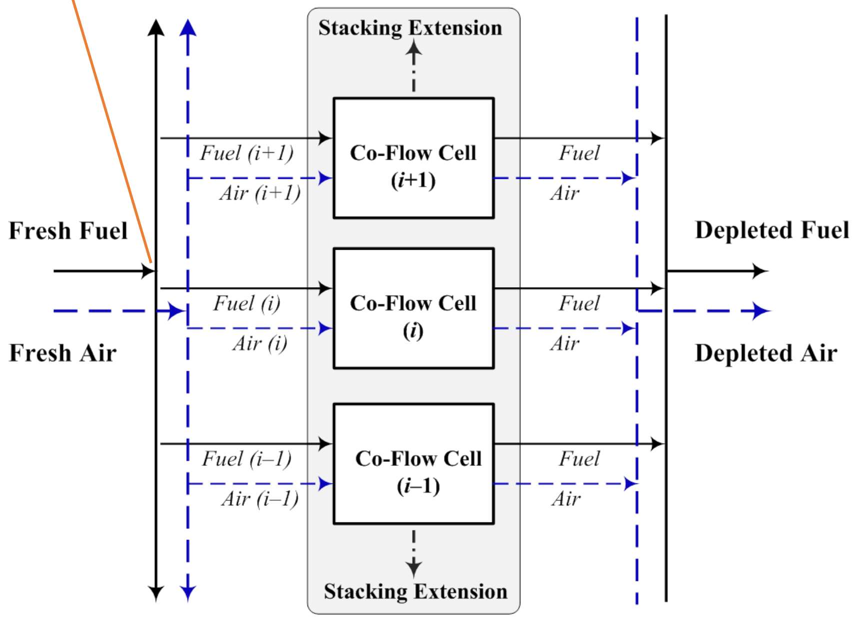
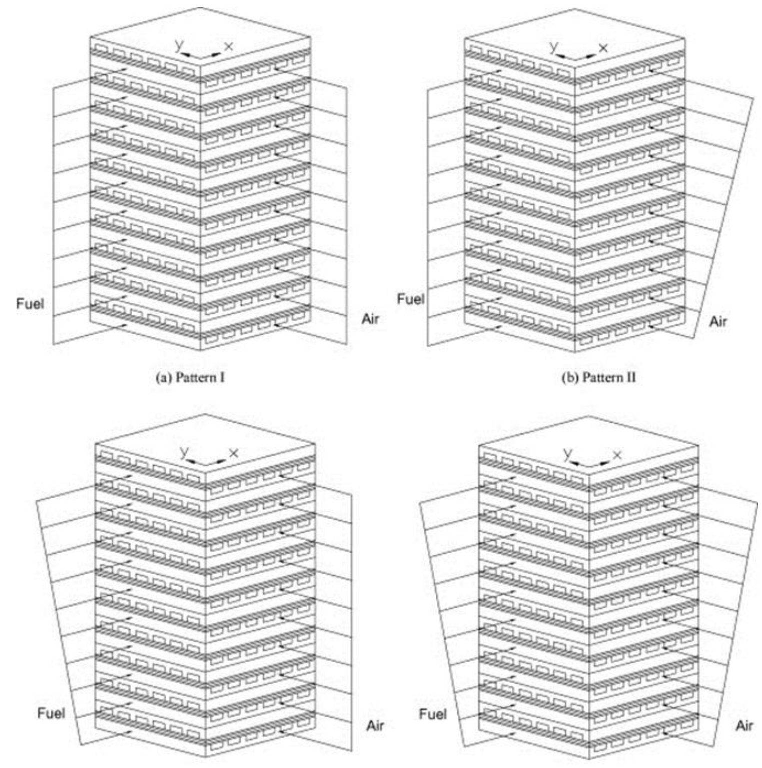
A stack analysis: effect of manifold maldistribution

$$f^n = \overline{f}\left(\frac{2d_{stack}}{(n_{stack}-1)}(n-1)+(1-d_{stack})\right)$$





(a) Pattern I (b) Pattern II (c) Pattern III (d) Pattern IV

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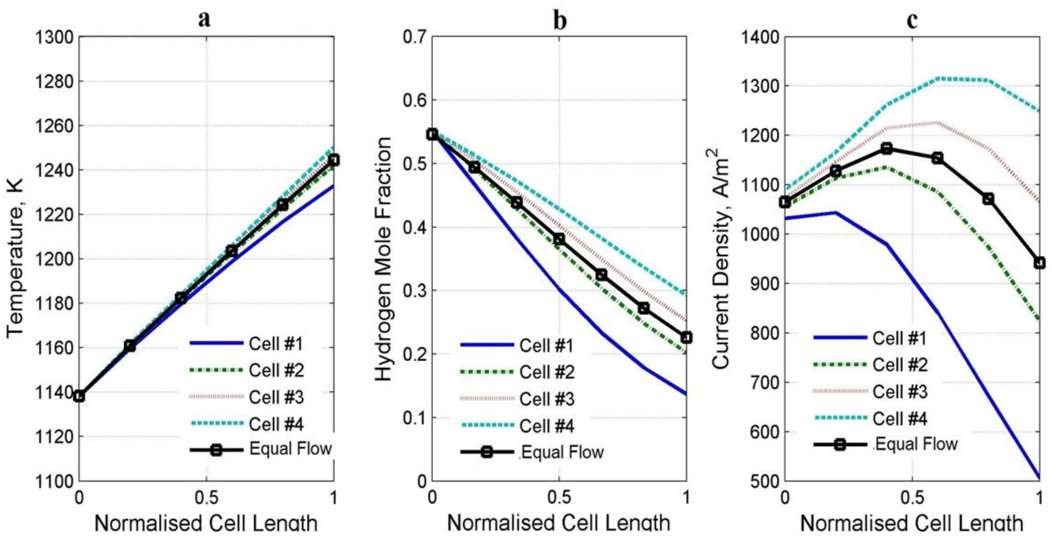
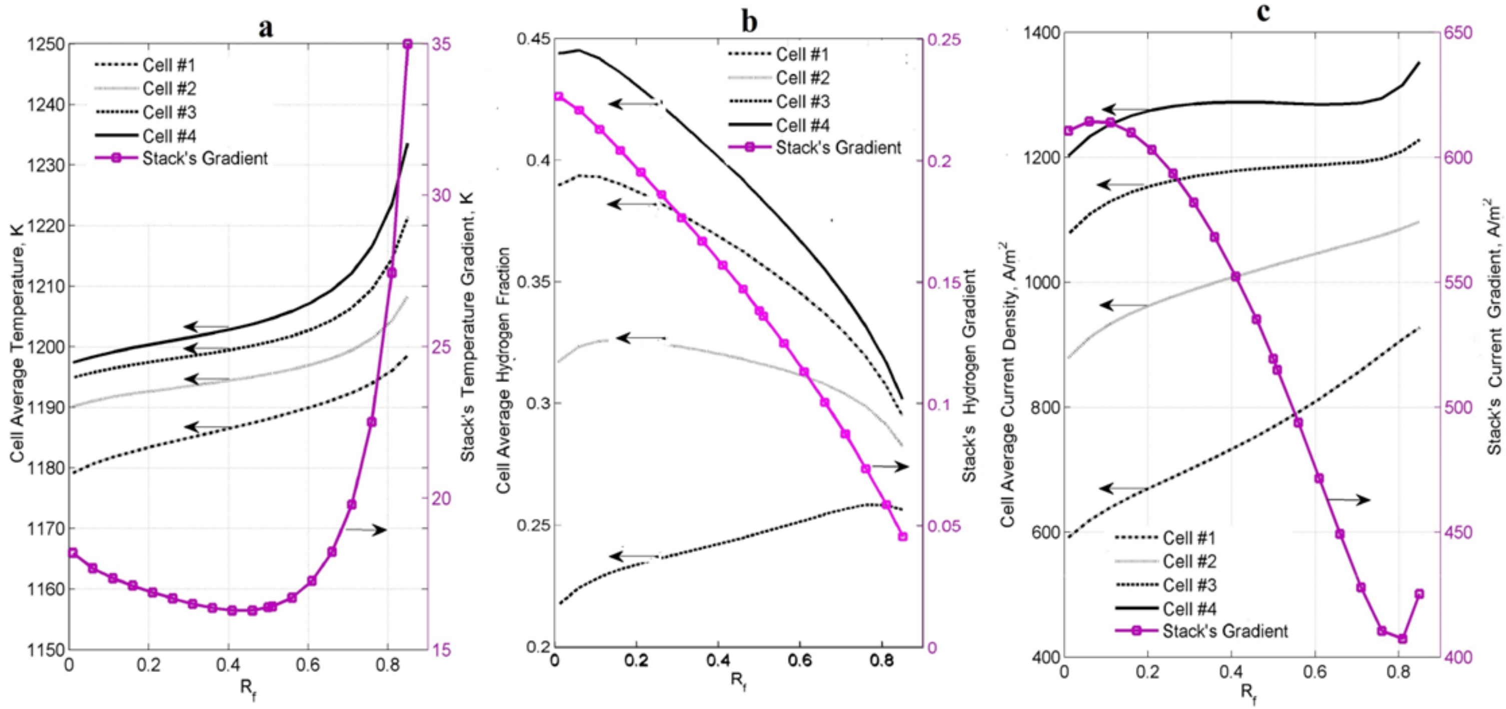
Cell-to-Cell variation of distributed variables caused by the fuel manifold malfunction

Significant deviation from even distribution

- The temperature of the cell with less fuel share is minimum but more smoother ;
- The generated current and average reactant availability are minimum in cell with min fuel share but not necessary result in smoother profile
- Current peaks in each cell are significantly shifted by fuel shares



Stacking direction gradients as a function of anode off-gas recycle (AOGR)



- AOGR rate has different effect on cells in stack depending on their fuel share;
- AOGR influences the gradient in stacking direction making room for optimization works for thermal management
- AOGR should be limited to due sizing and cost issues.

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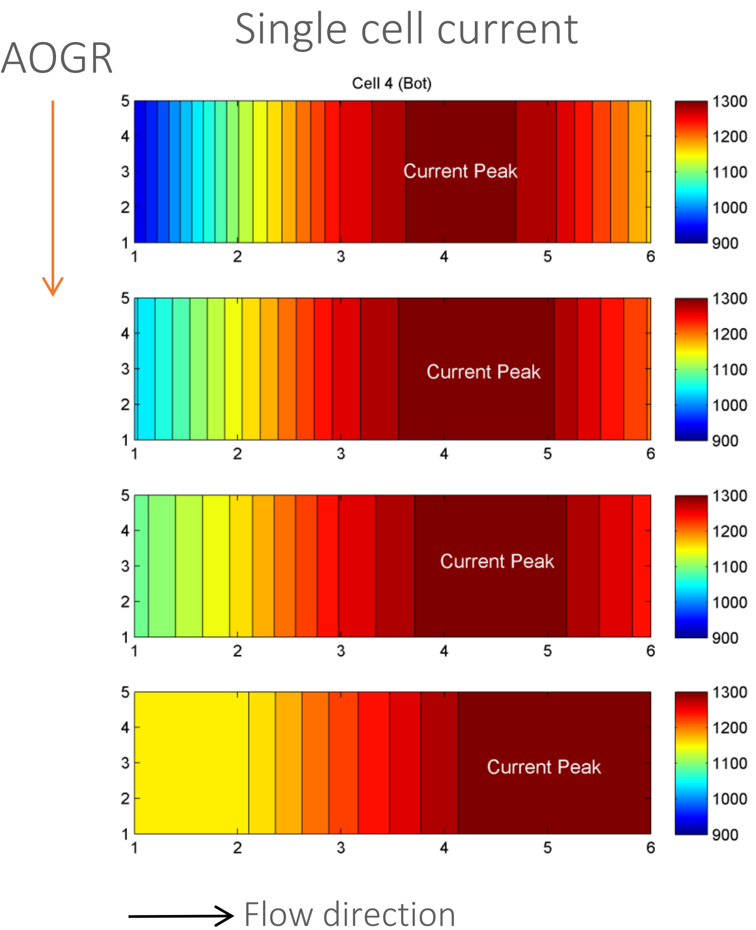
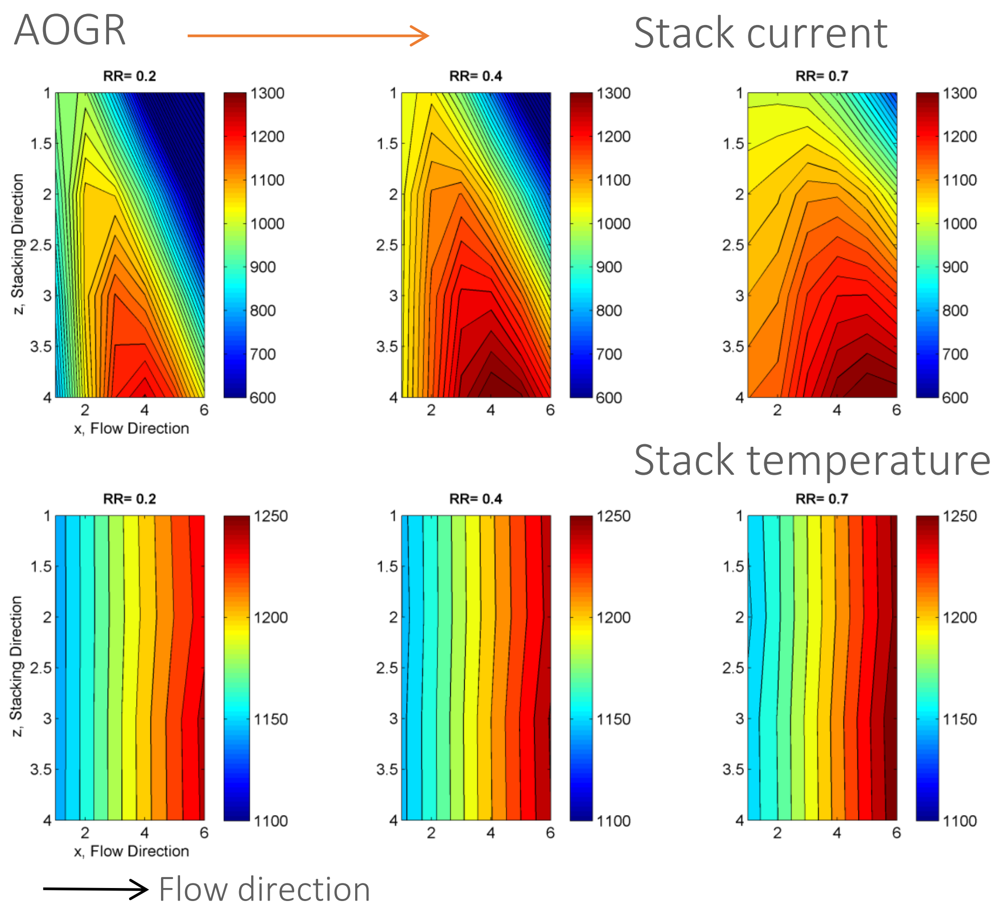
Counters for single cell unit and multi-cell stack under varying AOGR





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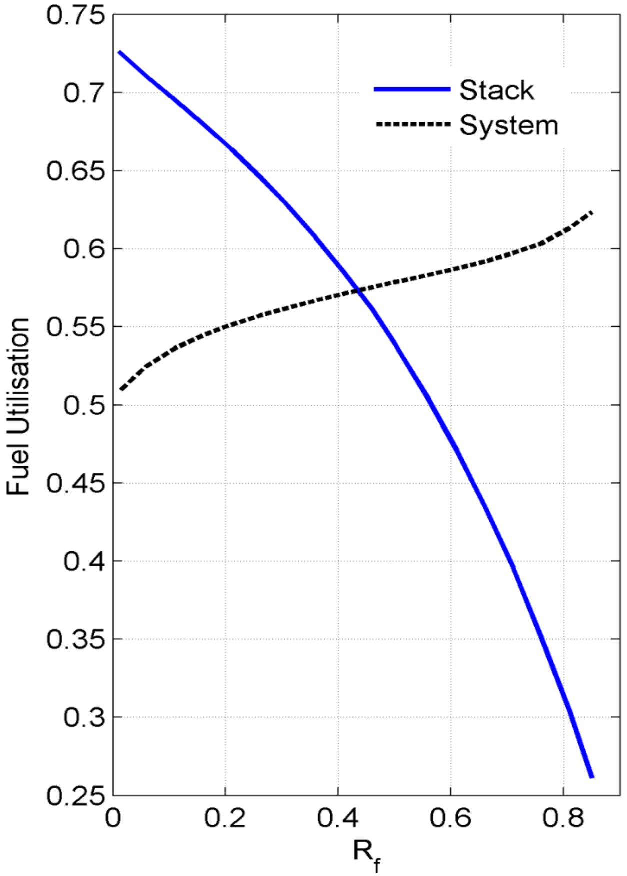
Process performance: Effect of recycle fraction on stack and system fuel utilisation

- AOGR reduces the fuel utilization in stack while increases that for whole system;
- This is technically desired because overall efficiency will be improved while stack/cell fuel starvation and hot spot formation can be avoided;
- Optimization of AOGR must be conducted through a detailed stack model integrated in a system level model such as this work.
- This optimization task is certainly a multi- objective one that leads in a so called “effective operation” not “most optimum operation” as it ultimately results in a compromised strategy.



Thank you for your attention!

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