Multi-scale Thermal Uniformity Optimization in Methane-Fueled Solid Oxide Fuel Cells (SOFCs)

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Group-5

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Academic Course Module: Thermodynamics 2 (MEEN2007W) & Mechanics of Fluids 2 (MEEN3005W)

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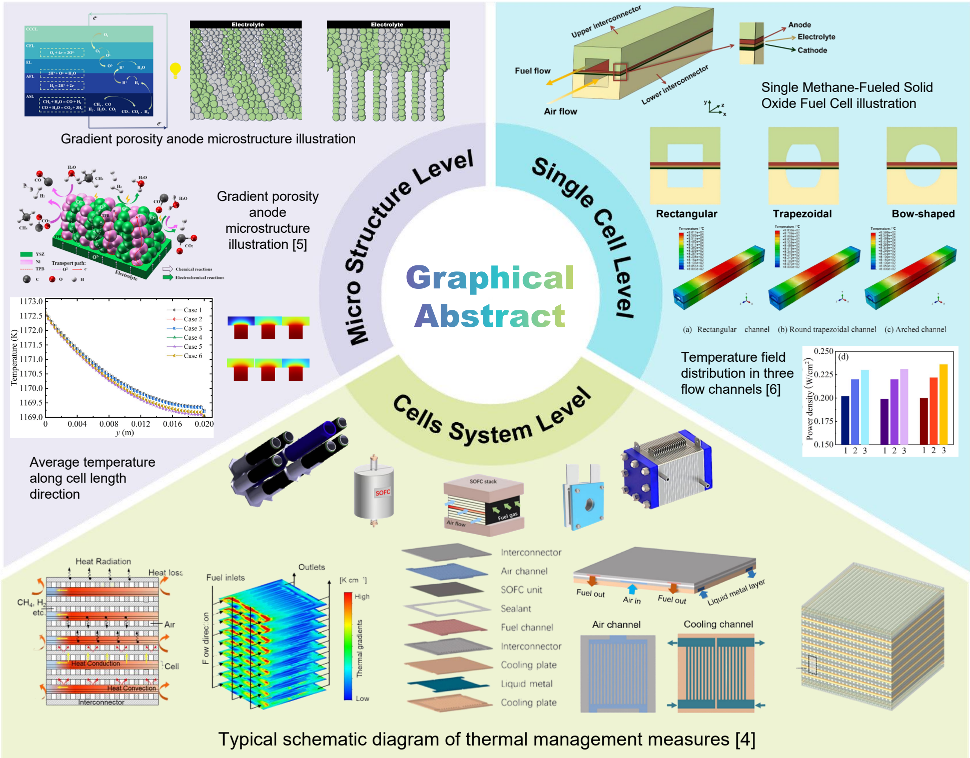
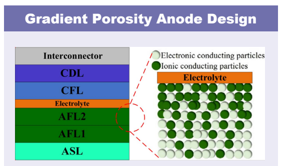


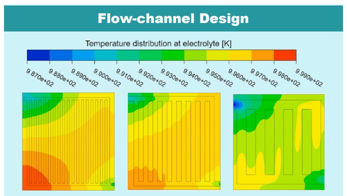
Recent Studies on Thermal Uniformity Improvment

Gradient Porosity Anode Design



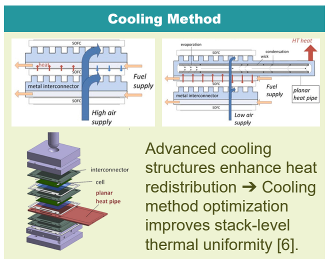
Gradient anode porosity changes gas diffusion and local heat generation ➔ Its effect on SOFC thermal uniformity is evaluated [2].

Flow-channel Design



Channel widths regulate reactant flow distribution ➔ Flow-channel design is a key route for thermal-uniformity improvement [5].

Cooling Method



Advanced cooling structures enhance heat redistribution ➔ Cooling method optimization improves stack-level thermal uniformity [6].

Introduction

➢ **What are Methane-Direct Solid Oxide Fuel Cells?**
It is a type of solid oxide fuel Cells that converts methane directly to electricity via internal reforming, without external reformers [2].

➢ **Why is thermal uniformity optimization important?**
It prevents thermal stress and material degradation caused by thermodynamic mismatch, ensuring long-term durability for Methane-Direct SOFCs [1].

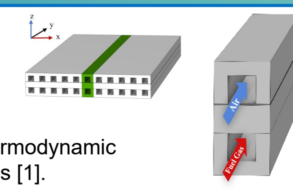


Figure 1. Schematic of a SOFCs stack and a single SOFC

➢ **What metrics are used to evaluate Thermal Uniformity?**

ΔT (T_{max} - T_{min})	Temperature Gradient	T_{max}
Temperature non-uniformity	Local thermal variation	Hotspot risk

Methodology Flow Chart

Multi-scale Optimization → Optimization Case Design → 3D Multi-physics Modeling → Simulation Results → Comparative Analysis

Figure 2. The SOFC physical diagram

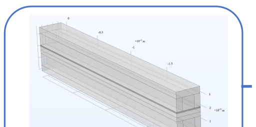


Figure 3. The 3D modeling of a SOFC

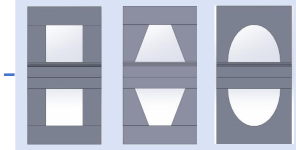
Governing Equations: Energy, species, charge, flow, and electrochemical reaction kinetics

Model verification & grid independence validation

Gradient anode porosity varies the pore fraction of the anode thickness to control gas diffusion & reaction distribution [2].

Porosity						
SOFC Anode	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
ASL 1	0.20	0.30	0.40	0.40	0.40	0.27
ASL 2	0.20	0.30	0.40	0.40	0.30	0.27
AFL 1	0.20	0.30	0.40	0.30	0.20	0.27
AFL 2	0.20	0.30	0.40	0.20	0.20	0.27

Flow-channel Architecture: Three channel configurations



Design target: balance current density and thermal uniformity

L_a
Bottom channel width
L_W
Top channel width

Figure 4. Three channel configurations

Representative cooling methods [4]

4 Cooling method	
Excess air cooling	Liquid cooling
Independent gas cooling	Heat pipe cooling

Method group	Typical medium
Gas cooling	Air / Argon
Liquid / pipe cooling	Water / liquid metals

Gas cooling ➔ simple and controllable heat removal
Liquid cooling ➔ strong cooling capacity for high heat load
Heat-pipe cooling ➔ passive heat redistribution

Simulation Result & Thermal Uniformity Analysis

Micro Structure Level

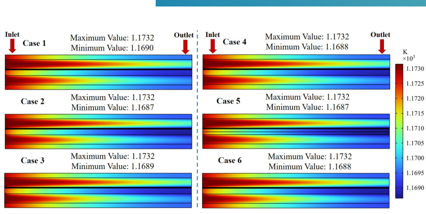


Figure 5. Temperature distribution along the cell length direction

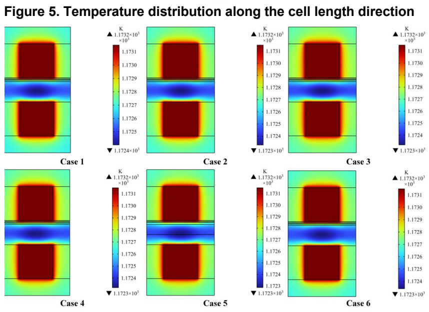


Figure 6. Temperature distribution at the inlet x-z cross-section

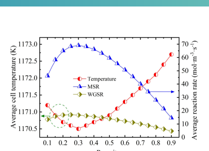


Figure 7. Average chemical reaction rates and temperature

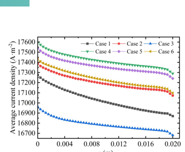


Figure 8. The distribution of current density

- ➢ Six anode porosity cases were compared: including **homogeneous** and **graded** anode designs.
- ➢ All cases show **similar** temperature trends along the cell length.
- ➢ Porosity distribution can change **local temperature distribution**.
- ➢ Case 1 gives the **lowest** ΔT **= 4.2K**, showing the best thermal uniformity.
- ➢ Gradient porosity is feasible, but highly **parameter-sensitive**.
- ➢ Current density decreases **downstream**, **Case 4** is highest.

Single Cell Level

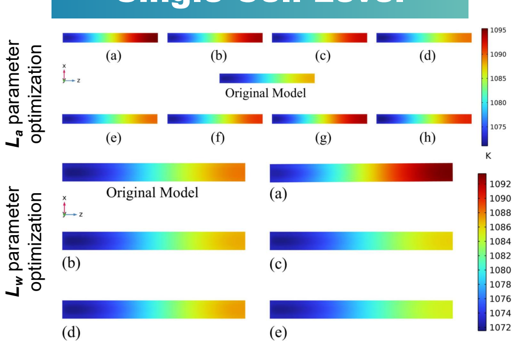


Figure 9. Temperature Distribution in Different Flow Channels (L_a & L_w)

- ➢ Specific **trapezoidal** and **bow-shaped** channels enhance current density by **15-16%** , intensified local reactions increase the ΔT by nearly **7 K** [3].
- ➢ When temperature regulation is prioritized , specific trapezoidal cross-sectional modifications can reduce the temperature gradient by **24%** at the expense of partial electrical performance [3].

Cells System Level

Cooling Method	Cooling Medium	$\Delta T / \left(\frac{\partial T}{\partial L}\right)_{before}$	$\Delta T / \left(\frac{\partial T}{\partial L}\right)_{after}$
Excess air cooling	Air	21 K cm⁻¹	14 K cm⁻¹
Independent gas cooling	Argon (Ar) and air	88.36 K	45.31 K
Liquid cooling	Pressurized water cooling (Planar stack)	185 K	26 K
	Pressurized water cooling (Tubular stack)	295 K	62 K
	Liquid tin (Sn)	60 K	15 K
Heat pipe cooling	Na (Planar stack)	43 K	15 K
	Na (Tubular cell)	31 K cm⁻¹	13 K cm⁻¹
	Not specified	111 K	25 K

- ➢ System-level thermal management, particularly **liquid cooling**, can significantly suppress the stack-level **temperature gradients** and maximum ΔT induced by direct internal reforming (DIR) [4].

Conclusions

- ➢ **Anode Porosity:** Improvement from the Micro-level ➔ Highly parameter-sensitive. Case 1 shows the best thermal uniformity, with the lowest ΔT **= 4.2 K**.
- ➢ **Flow-channel:** Transport enhanced ➔ Performance vs. ΔT trade-off. Trapezoidal and bow-shaped improve current density by **15-16%**, but increase local ΔT by nearly **7 K**, and optimized trapezoidal channel can reduce temperature gradient by **24%**.
- ➢ **System cooling:** External complement ➔ Achieves overoll improvement. Liquid cooling significantly reduces stack thermal gradients, lowering ΔT to **26 K**.

Trade-off & Future Work

- ➢ **Methane-specific Focus:** While existing literature predominantly addresses general SOFCs, dedicated thermal management mechanisms tailored for methane-fueled SOFCs are urgently required.
- ➢ **Cross-scale Synergy:** Transitioning from single-scale studies to deeply coupling anode porosity, flow-channel architecture, and system-level thermal management.
- ➢ **Comprehensive Evaluation:** Expanding beyond the sole metric of thermal uniformity to comprehensively incorporate long-term durability and manufacturing cost assessments.

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