

# **BUILDING TRUST IN BATTERY MODELS:**

# **STANDARDISING MODEL VALIDATION THROUGH THERMAL-AWARE FRAMEWORKS**

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# Agenda

- Motivation and problem statement
- Thermal environment characterisation (dummy vs. real cells)
- Cooling-dependent results (convection, base, insulated)
- Impact on ECM validation
- Integration into a thermal-aware validation framework

# BATTERY MODEL VALIDATION STANDARDS



# Challenge Statement: Overarching

Tailoring validation methods to end-user requirements

Validating models for specific applications

Moving beyond single headline performance figures

Ensuring validation processes are reproducible

# Challenge Statement: Thermal Focus

Tailoring validation methods to end-user requirements

*Impact of differing thermal control methods on validation data and model performance.*

*Standard Operating Procedures for end-users will be a key project output.*

Validating models for specific applications

*Thermal environment parameterisation.*

*The work will feed into the Standard Operating Procedures.*

Moving beyond single headline performance figures

*Decoupling the thermal error from model error*

Ensuring validation processes are reproducible

*Standard Operating Procedures, based upon the thermal control available to the experimentalist conducting the validation.*

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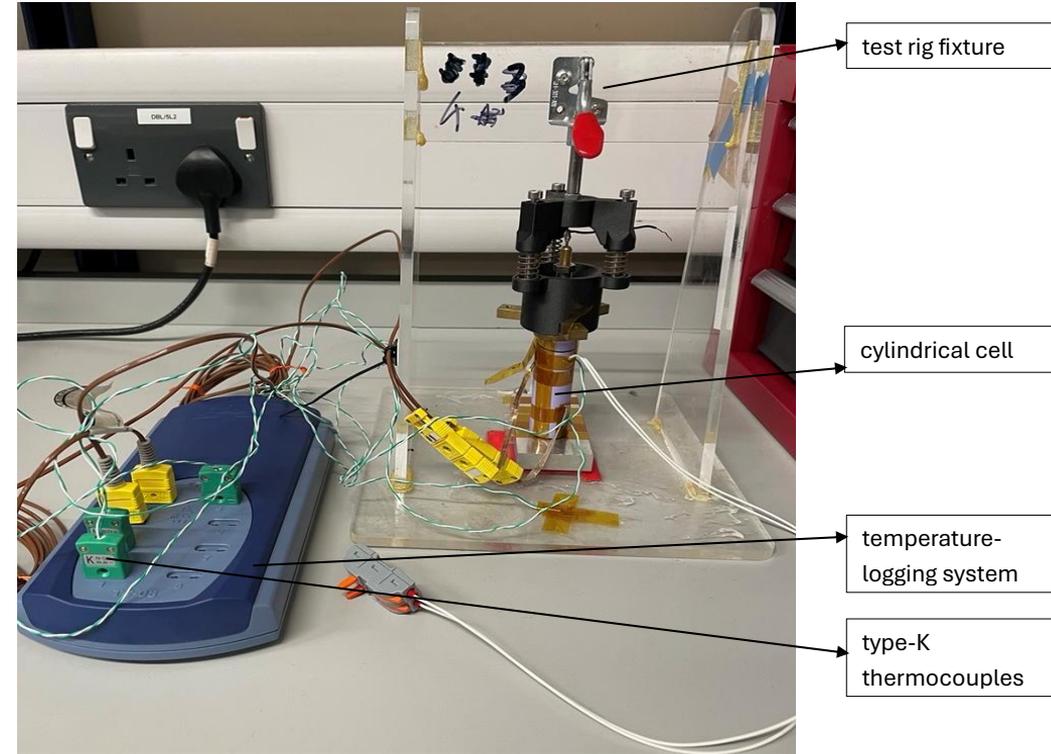
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# THERMAL ENVIRONMENT CHARACTERISATION



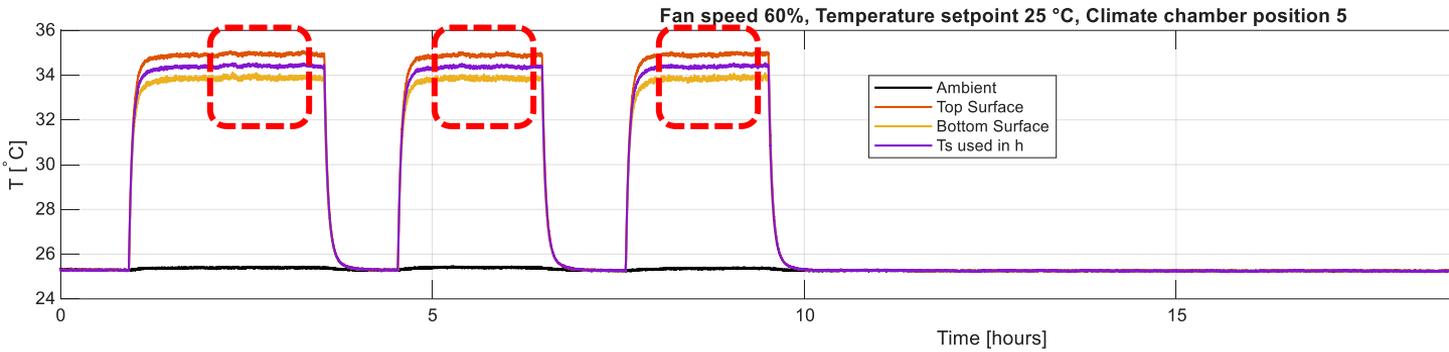
# Convection-Cooled Setup



# Impact of Thermal Management Strategy

	Cylindrical dummy cell with resistive heater			Cylindrical LGM50LT cells
<b>Convection-cooled</b> (in the climate chamber)	Climate chamber position: • <b>1</b> , 100%, 25 °C • <b>3</b> , 100%, 25 °C • <b>5</b> , 100%, 25 °C	Fan speed: • <b>5</b> , <b>100%</b> , 25 °C • <b>5</b> , <b>60%</b> , 25 °C • <b>5</b> , <b>40%</b> , 25 °C	Temperature setpoint: • <b>5</b> , 100%, <b>0 °C</b> • <b>5</b> , 100%, <b>10 °C</b> • <b>5</b> , 100%, <b>25 °C</b>	Cell-to-cell and chamber position variability: • <b>1</b> , 100%, 10 °C • <b>2</b> , 100%, 10 °C • <b>3</b> , 100%, 10 °C • <b>4</b> , 100%, 10 °C
<b>Fully insulated</b> (in the climate chamber)	N/A			Cell-to-cell and chamber position variability: • <b>1</b> , 100%, 10 °C • <b>2</b> , 100%, 10 °C • <b>3</b> , 100%, 10 °C • <b>4</b> , 100%, 10 °C
<b>Base-cooled</b>	Temperature setpoint: • <b>25 °C</b>			Cell-to-cell variability at two temperature setpoint: • <b>1</b> , 100%, <b>10 °C</b> • <b>1</b> , 100%, <b>25 °C</b> • <b>2</b> , 100%, <b>10 °C</b> • <b>2</b> , 100%, <b>25 °C</b> • <b>3</b> , 100%, <b>10 °C</b> • <b>3</b> , 100%, <b>25 °C</b> • <b>4</b> , 100%, <b>10 °C</b> • <b>4</b> , 100%, <b>25 °C</b>

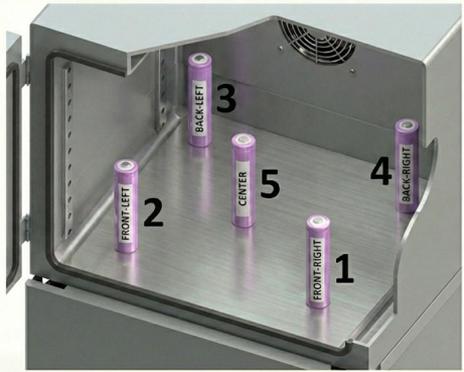
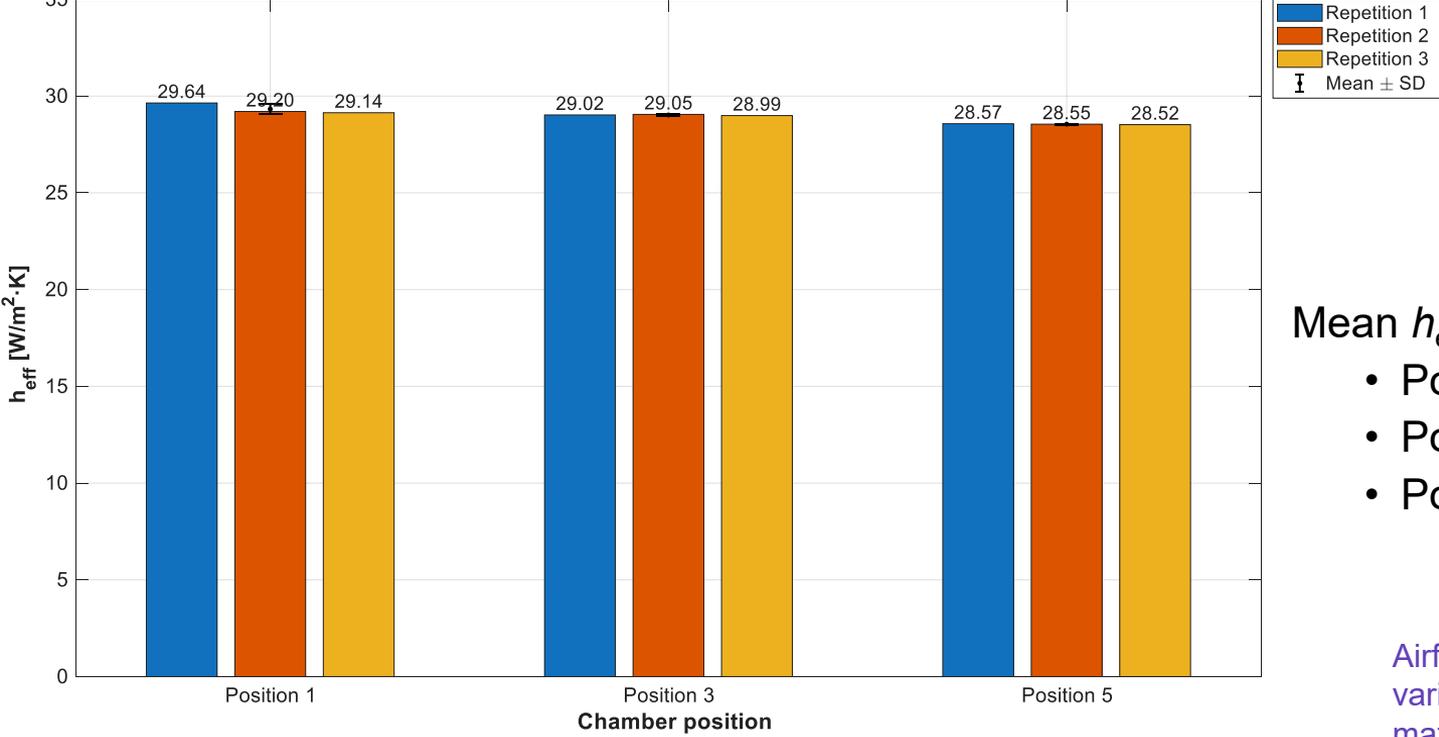
# Experimental Methodology: Cylindrical dummy cell with internal resistive heater (1 W)



- 3 repeats per condition (steady-state verified).
- $\geq 2$  h heating +  $\geq 1$  h rest per cycle.
- Mean external surface temperature used to evaluate  $h_{\text{eff}}$ .
- $h_{\text{eff}}$  determined via standard convective heat transfer formulation.

# Dummy Cell: Convection-Cooled Setup

Effective heat transfer coefficient vs chamber position at a 25 °C chamber temperature setpoint (Fan speed of 100%)



Mean  $h_{eff}$  (same test rig):

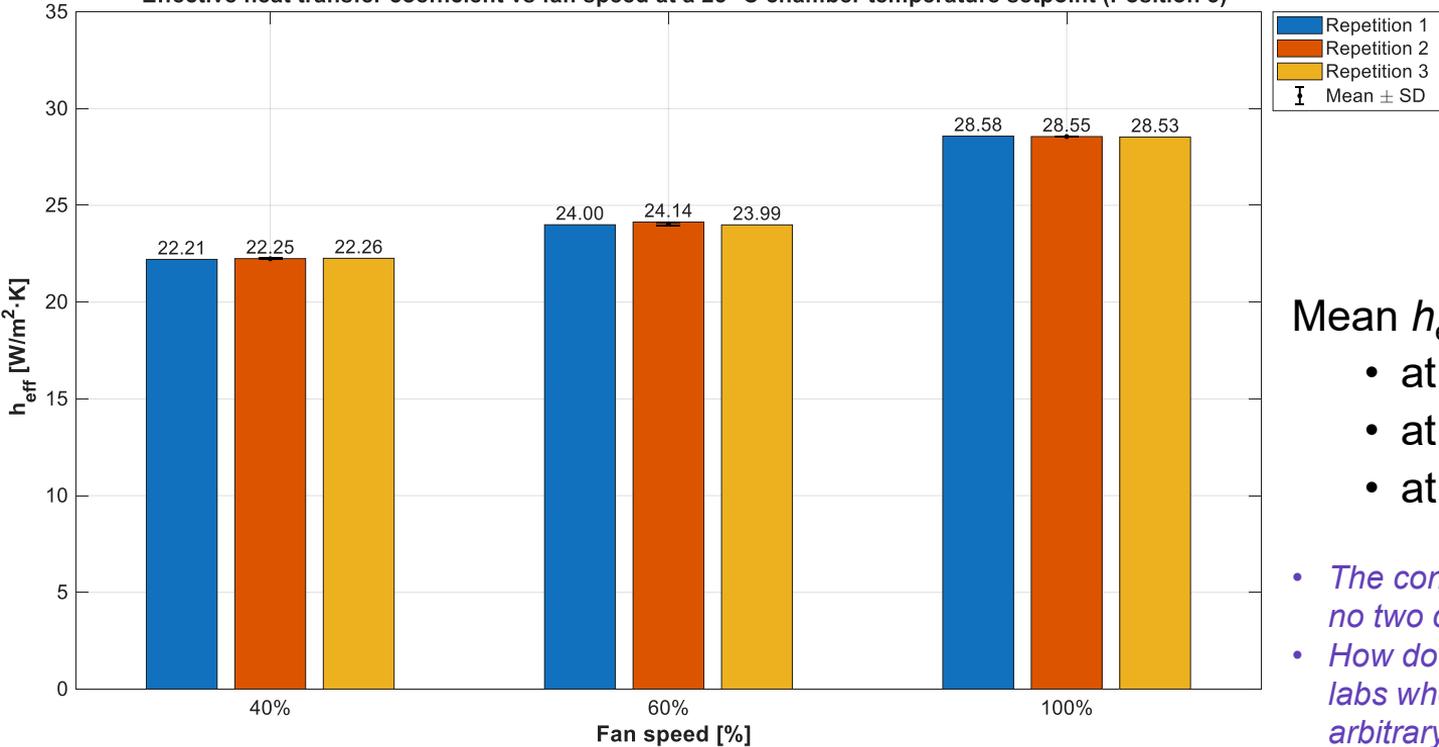
- Position 1: 29.33 W·m<sup>-2</sup>·K<sup>-1</sup>
- Position 2: 29.02 W·m<sup>-2</sup>·K<sup>-1</sup>
- Position 3: 28.55 W·m<sup>-2</sup>·K<sup>-1</sup>

Airflow is highly uniform (~3% variation); small differences may matter at high heat loads.

- Chamber position effects are small (~2.7%).
- Repeatability within each position is <0.5%.

# Dummy Cell: Convection-Cooled Setup

Effective heat transfer coefficient vs fan speed at a 25 °C chamber temperature setpoint (Position 5)



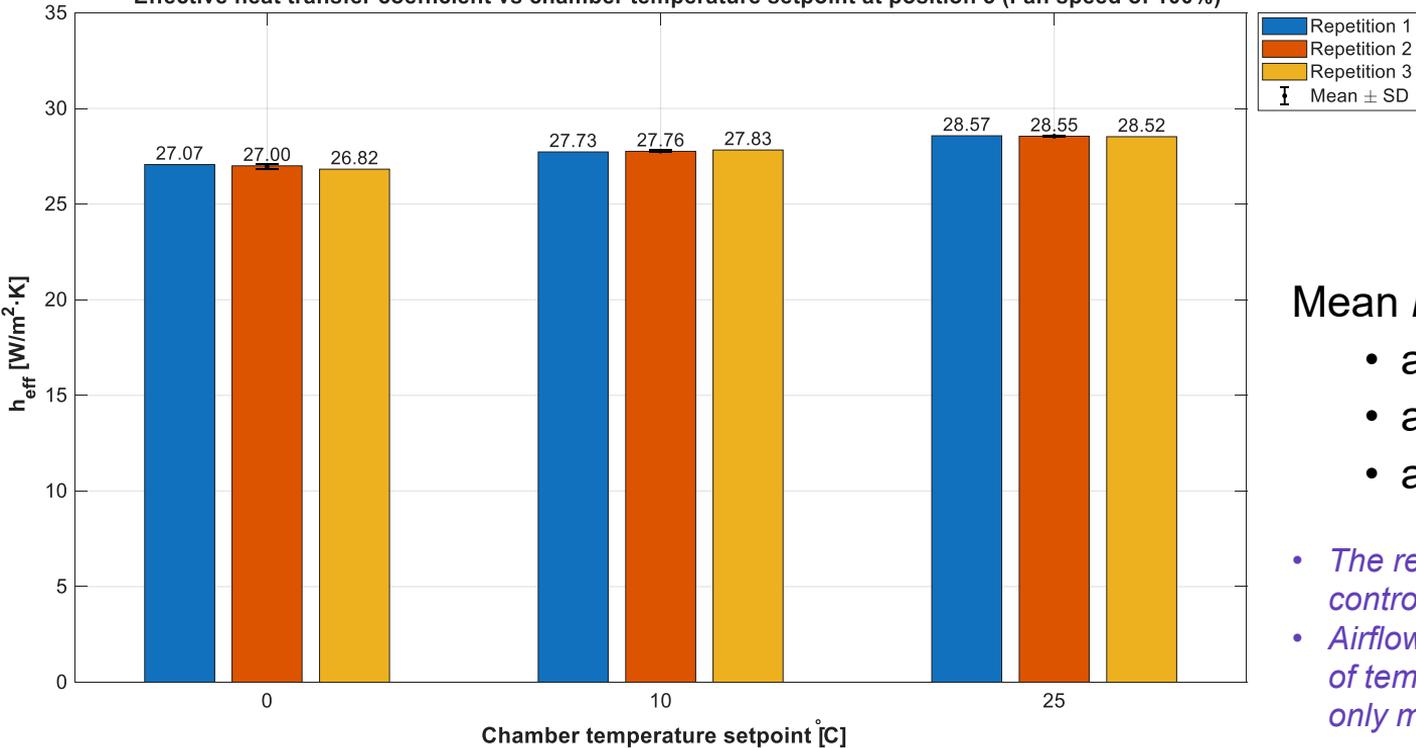
Mean  $h_{\text{eff}}$  (same test rig):

- at 40%: 22.24 W·m<sup>-2</sup>·K<sup>-1</sup>
  - at 60%: 24.04 W·m<sup>-2</sup>·K<sup>-1</sup>
  - at 100%: 28.55 W·m<sup>-2</sup>·K<sup>-1</sup>
- The concern raised by this result is that no two climate chambers are the same.*
- How do you provide traceability across labs when you are discussing just an arbitrary fan speed % value?*

- Fan speed effects are significant (~**28.4%** increase in  $h_{\text{eff}}$  when increasing from 40% → 100%).
- Repeatability within each fan-speed condition is ≤ ~**0.7%**, confirming strong experimental robustness.

# Dummy Cell: Convection-Cooled Setup

Effective heat transfer coefficient vs chamber temperature setpoint at position 5 (Fan speed of 100%)



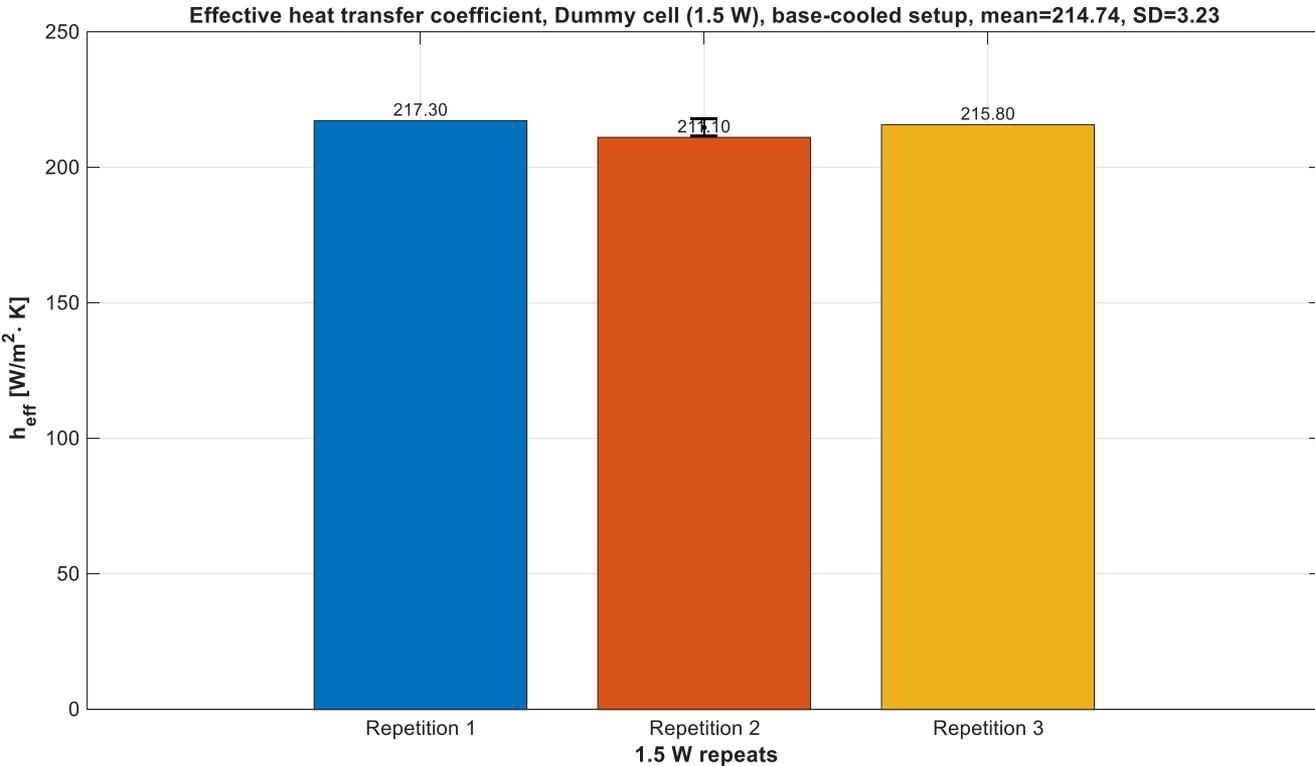
Mean  $h_{\text{eff}}$  (same test rig):

- at 0 °C : 26.96 W·m<sup>-2</sup>·K<sup>-1</sup>
- at 10 °C : 27.77 W·m<sup>-2</sup>·K<sup>-1</sup>
- at 25 °C : 28.55 W·m<sup>-2</sup>·K<sup>-1</sup>

- *The results indicate stable and well-controlled climate chamber performance.*
- *Airflow remains effectively independent of temperature, as air properties vary only marginally over the tested range.*

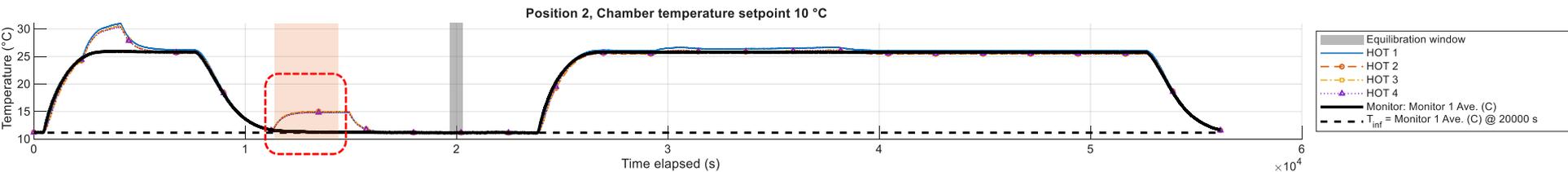
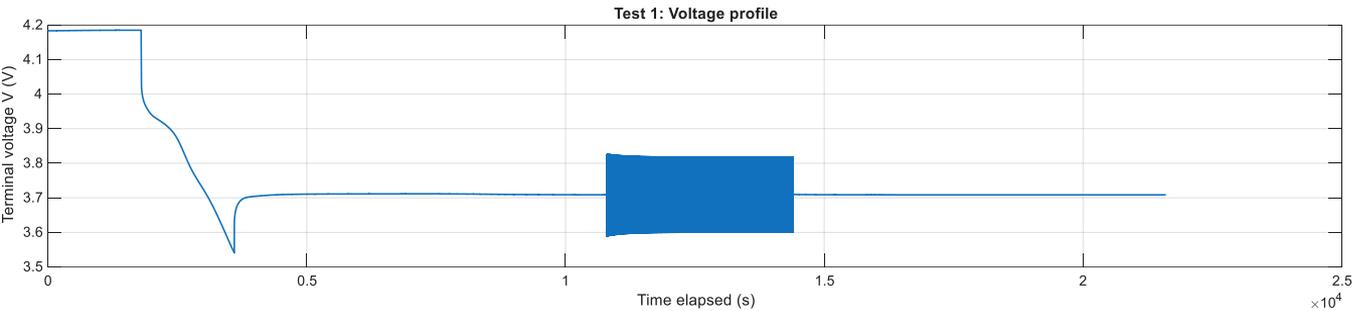
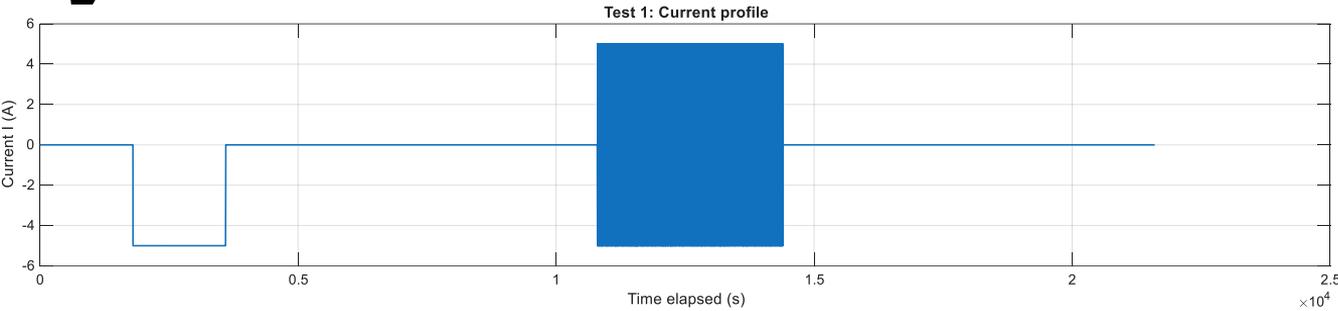
- Chamber temperature introduces limited variation (~**5.9%** increase in  $h_{\text{eff}}$  from 0 → 25 °C).
- Repeatability in each condition is **≤0.5%**, supporting reduced repetition in future tests.
- Thermal boundary is weakly temperature-dependent under forced convection (0–25 °C).

# Dummy Cell: Base-Cooled Setup (25 °C)



- The base-cooled setup yields a mean effective heat transfer coefficient of  $h_{\text{eff}}=214.74 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ .
- Heat removal capability is **~7.5× greater** than the convection-cooled setup at 25 °C (100% fan).
- Thermal boundary is conduction-dominated and highly stable, with **≤1.7%** maximum deviation across repeated tests (same test rig).

# Experimental Methodology: Cylindrical LGM50LT cells

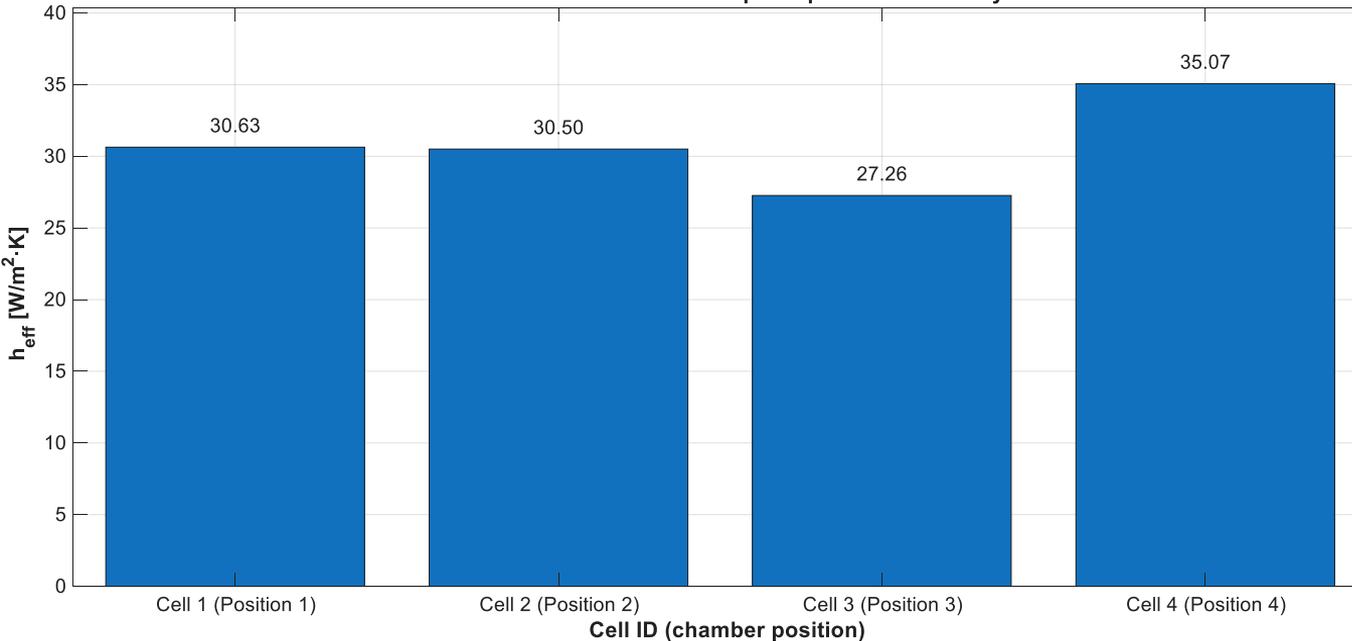


- Thermal pulse test at 50% SoC.
- 1C discharge/charge pulses (1 s each) for 1 h (1800 cycles).
- Pulsed loading ensures thermal equilibrium with defined heat generation.
- $h_{\text{eff}}$  evaluated using mean external surface temperature.

# LGM50LT cells - Convection-cooled (10 °C)

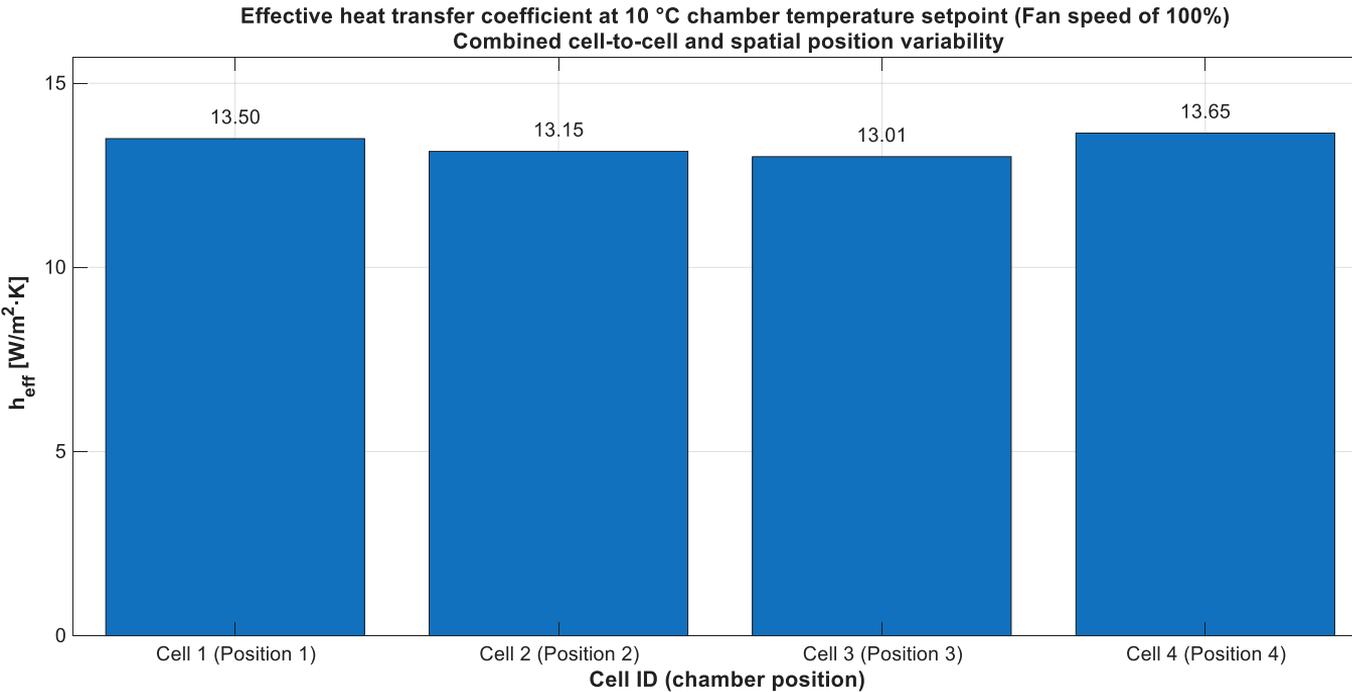
Effective heat transfer coefficient at 10 °C chamber temperature setpoint (Fan speed of 100%)

Combined cell-to-cell and spatial position variability



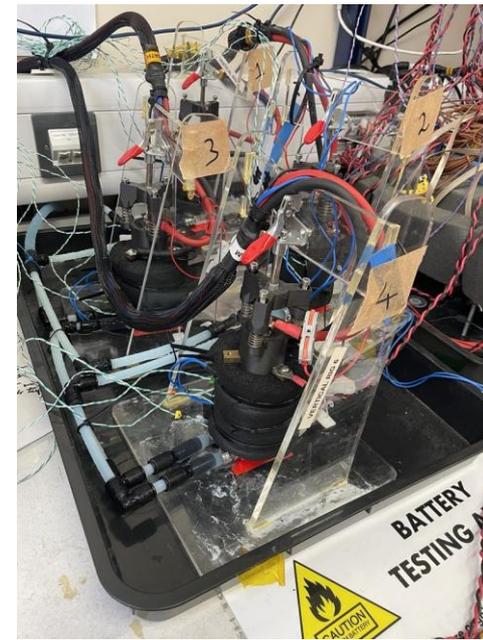
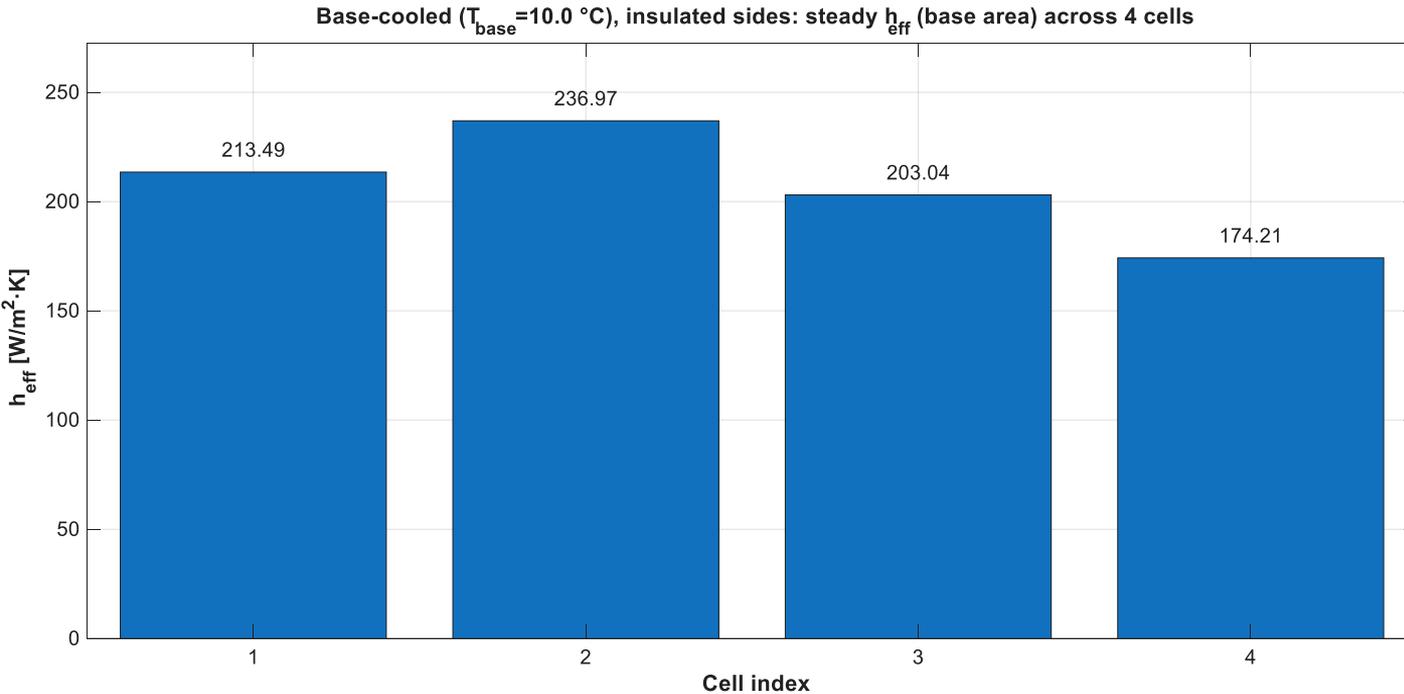
- Despite cell-to-cell and positional variability, the mean  $h_{\text{eff}}$  ( $30.87 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ) is comparable to the convection-cooled dummy-cell results.
- Under the tested forced-convection conditions, the dummy-cell methodology appears representative of real-cell behaviour.
- The applied square-wave pulse profile is suitable for controlled heat generation in real-cell testing.

# LGM50LT cells - Fully insulated (10 °C)



- Cell-to-cell and positional variability is low (**~4.7%**).
- Despite full insulation, a finite heat transfer coefficient ( $\sim 13.3 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ) persists, reflecting residual heat dissipation through conduction and limited natural convection pathways.

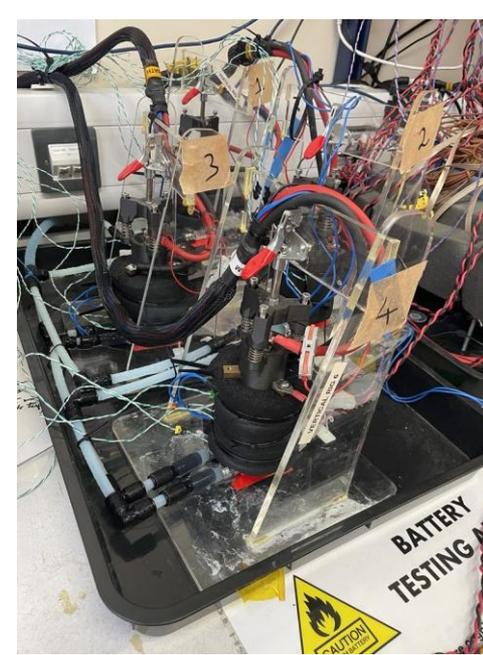
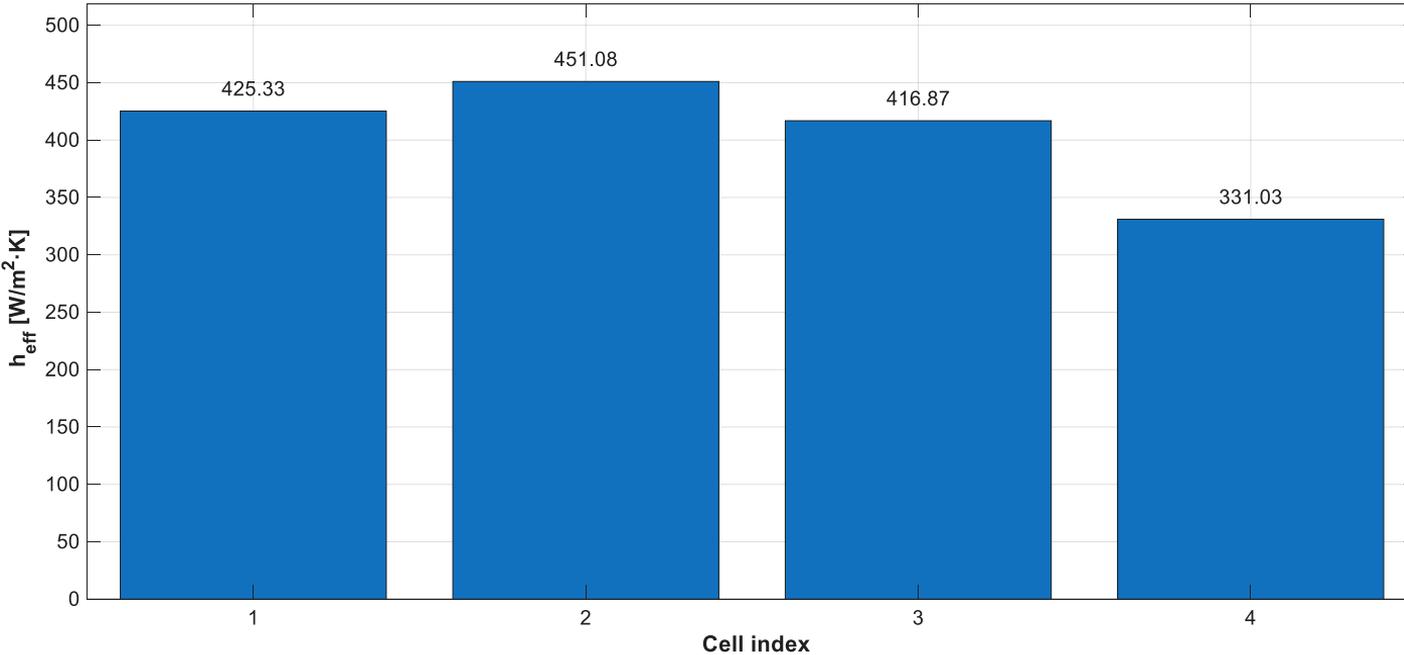
# LGM50LT cells - Base-cooled (10 °C)



- Base-cooled configuration yields high heat transfer coefficients (mean  $\approx 206.9 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ ), confirming dominant conductive heat removal through the cooled base plate.
- Cell-to-cell variability is  **$\sim 26.5\%$** , larger than in convection-cooled tests, indicating sensitivity to thermal contact resistance and mounting pressure.

# LGM50LT cells - Base-cooled (25 °C)

Base-cooled ( $T_{\text{base}}=25.0\text{ °C}$ ), insulated sides: steady  $h_{\text{eff}}$  (base area) across 4 cells



- High  $h_{\text{eff}}$  (mean  $\approx 406.1\text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ) confirms conduction-dominated heat removal through the base plate.
- Cell-to-cell variability is  $\sim 26.6\%$ , larger than in convection-cooled tests, indicating sensitivity to thermal contact resistance and clamping pressure.
- Higher values than the dummy cell indicate additional pathways influencing heat extraction under base-cooled conditions.

# What This Means for Industry and Model Validators

- Cooling strategy can change the effective heat transfer coefficient by an order of magnitude.
- Thermal boundary differences can be misinterpreted as model deficiencies.
- Fan speed %, chamber configuration and mounting pressure are not directly transferable across labs.

## Risk

*Model validation without explicit thermal characterisation can lead to misleading performance conclusions.*

## Opportunity

*Embedding effective thermal resistance into validation workflows enables:*

- *Fair comparison between labs*
- *SOP-aligned validation*
- *More defensible model approval decisions*

# Next Steps (Towards Standardisation)

- Integrate the experimentally derived effective thermal resistance into the ECM to explicitly capture thermal–electrical coupling under WLTP cycles.
- Implement the effective temperature formulation within the HOT framework to decouple thermal error from intrinsic model error.
- Quantify the impact of thermal representation on validation metrics (e.g., voltage RMSE) across cooling configurations.
- Investigate additional heat-transfer pathways (e.g., through the brass connection block) to explain deviations between real and dummy cells under base-cooled conditions.

# QUESTIONS/ FEEDBACK/ AOB

[bristol.ac.uk](http://bristol.ac.uk)

