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# CFD parametric optimization of a Direct Liquid Cooling based prototype for HEV/EV

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# OUR TECHNOLOGICAL OFFER

# From powder to power

01

NEW **BATTERY TECHNOLOGIES** AND MATERIALS

02

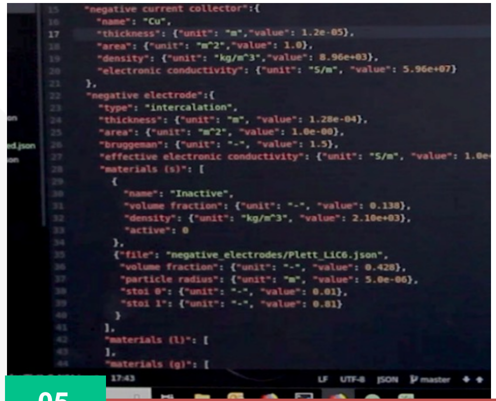
**MANUFACTURING** – BATTERY CELL PILOT LINE

03

**BATTERY SYSTEMS** - MODULE & PACK ENGINEERING

04

**ENERGY STORAGE** APPLICATIONS



05

**DIGITALIZATION**: MODELLING & SIMULATION

06

**BATTERY TESTING** & CHARACTERIZATION

Electromobility | Energy storage | Smart Grids | Cell manufacturers | Materials industry

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## Contents

# General overview

## Technological contextualization

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Thermal management of the battery system

Safety
Performance
Ageing

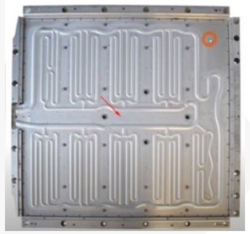
- More installed power / Energy
- Consumption / Cost reduction
- Increase battery lifetime
- Extreme environments

Current operational demands

Thermal management strategies to ensure the best conditions

**Indirect** liquid cooling

- High TRL
- Compact design
- High heat transfer capacity
- High control in low/medium power



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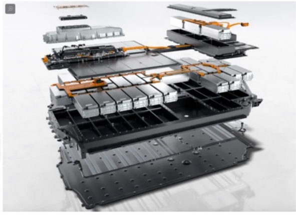
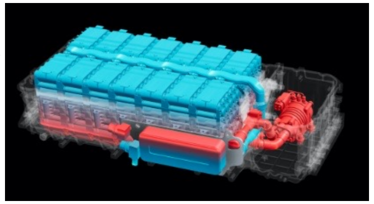


e-tron

**Direct** liquid cooling

- Direct contact
- Low environmental impact
- Security (TR)
- High heat transfer capacity
- Thermal control

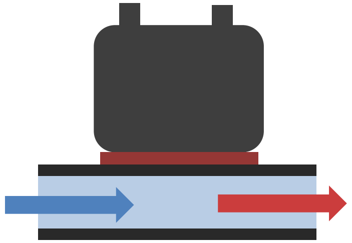

AMG



# General overview

## Strategy selection

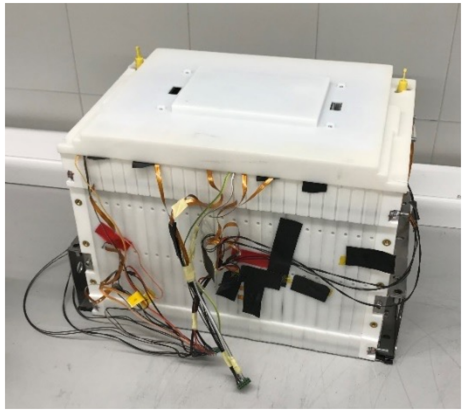
### Indirect Liquid Cooling (ILC)



Pumped One phase

Nowadays most used strategy
System implementation easiness
High performance at low C-rates

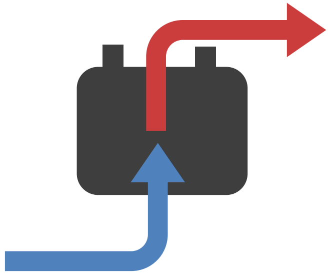
### vs



**CIDETEC battery module**

| | |
|---|---|
| Cell | 60Ah<br>Pouch Type<br>NMC Chemistry |
| Module | 24 Cells<br>12S2P electrical configuration |

### Partial Direct Liquid Cooling (DLC)



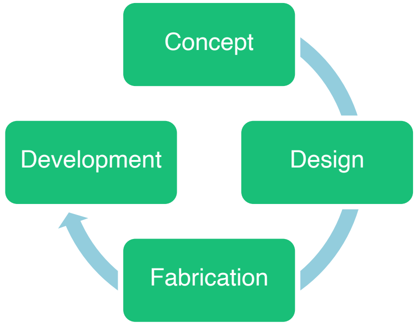
Pumped One phase

High potential strategy
Market dielectric fluids variety
Affordable application of DLC
High performance at high C-rates

Different cooling strategies in the same reference module

# General overview

## Prototype development

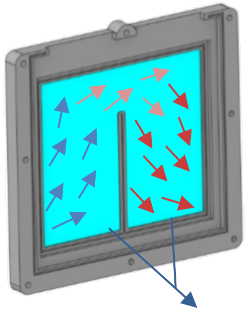



**Objective:**

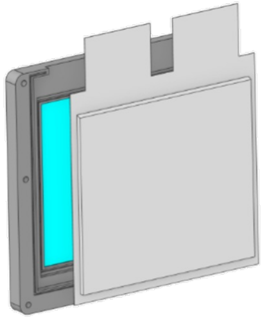
Develop a cell level scalable prototype based on the partial direct liquid cooling concept for large scale pouch type cells.

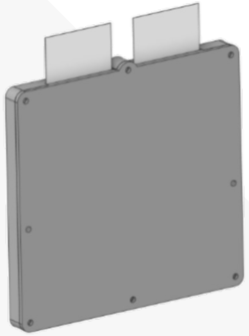
**Process**

- Design of the partial DLC concept
- Fabrication of the components
- Prototype development



Fluid flow

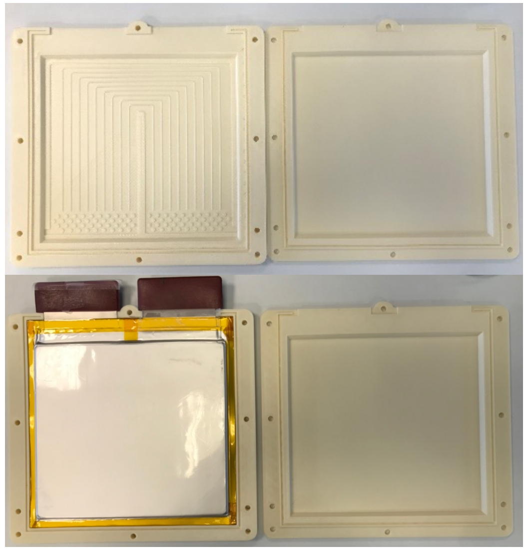


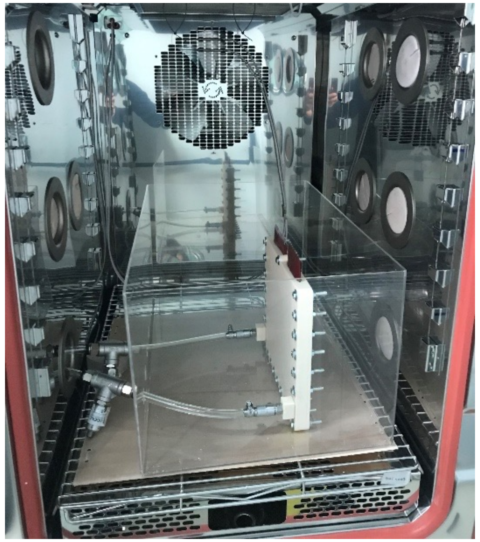


- Flow pattern
- Geometrical constrains
- Assembly
- Joining's
- Tolerances
- Cell geometry
- Alf position
- Tab dimensions
- Sealing component spaces
- …


Additive manufacturing

An accurate process to fabricate prototypes





**01** **<u>Design</u> of the cooling components**

**02** **Definition of the <u>fabrication process</u>**

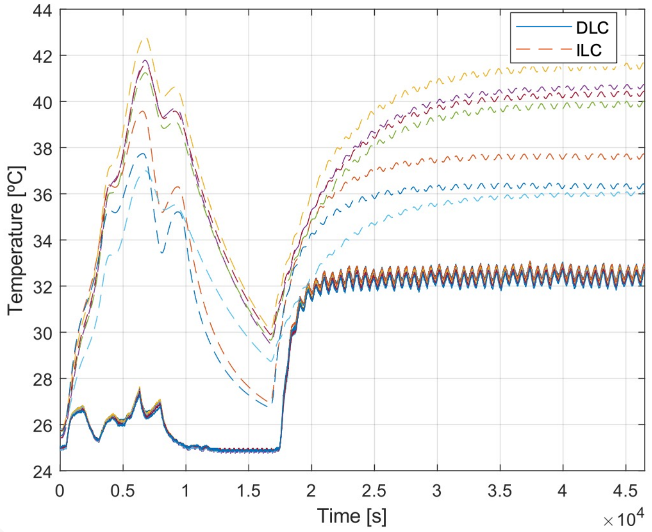
**03** **<u>Component</u> fabrication**

**04** **<u>Testing</u> process**

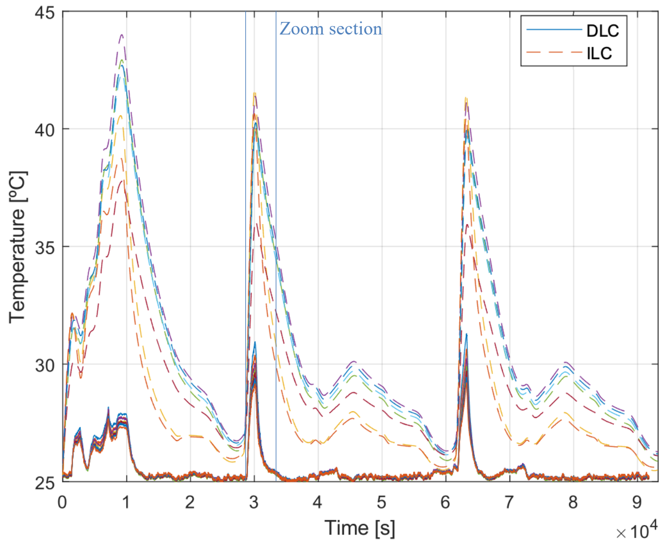
# General overview

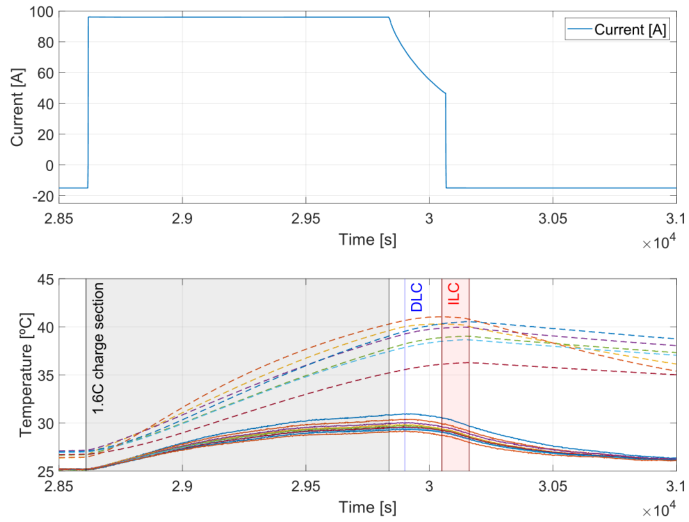
## Experimental comparison

SteadyState - 1C Pulses




Transient - 1,6C semi-fast charges




DLC vs ILC comparison at same **working conditions** and based on the pumping power **consumption criterion.**

- Comparing DLC results to ILC results, at steady-state 1C pulse tests $T_{max}$ decreases from 41.7 ºC to 32.6 ºC while $\Delta T$ dropped from 5.7 ºC to 0.4 ºC.
- After semi-fast charges the proposed DLC strategy is able to recondition cell temperature to the cooling set point.
- The influence of the insulation components in ILC is more relevant than the performance of the fluid in DLC.

## Contents

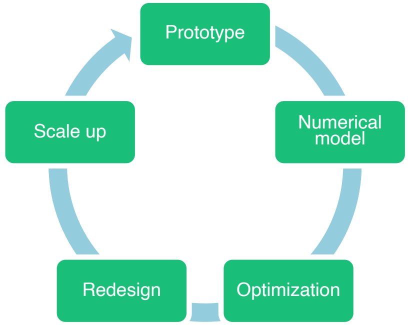
# Optimization process and results

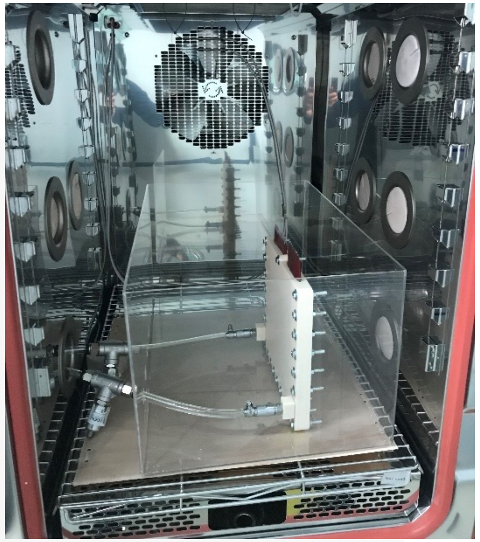
## Optimization process scope

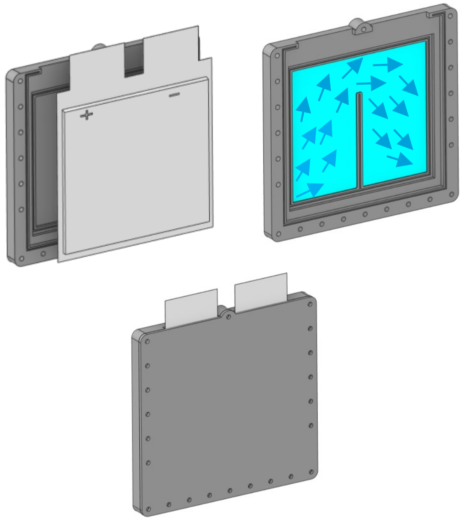
Objective:
Optimize the design of the cell level prototype before scaling up to a module level.

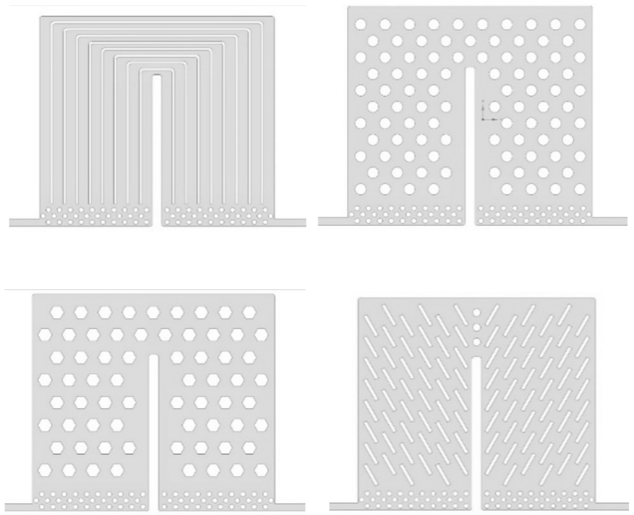
**Process**

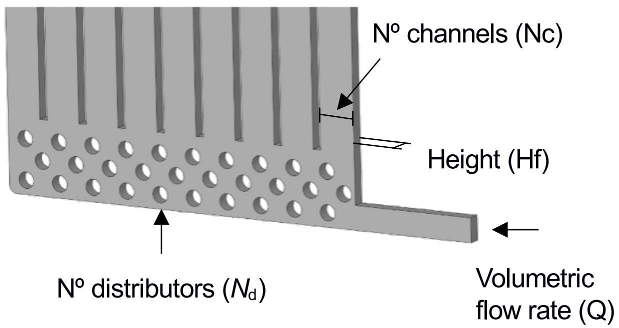
- Cell level numerical model
- Flowfield analysis
- Customized parametric optimization










2 level full factorial DOE — 4 variables to analyse

$2^4$ combinations to simulate

**01** **Reference prototype**

**02** **Simulation model development**

**03** **Flow pattern design selection**

**04** **Parametric design optization**

# Optimization process and results

## Numerical design and simulation model validation

Objective:

Define the battery cell heat generation model to characterize the thermal heterogeneity of the reference cell.

### General

- Domain: ANSYS Fluent
- Methodology: MSMD - ECM

### Data source

- Intrinsic characteristics
- HPPC tests
- Entropic heat

### Boundary conditions

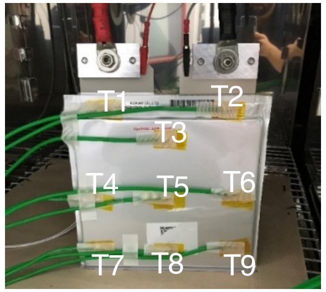
- Cell body: Adiabatic
- Tabs and clamps: 25 W/m²K

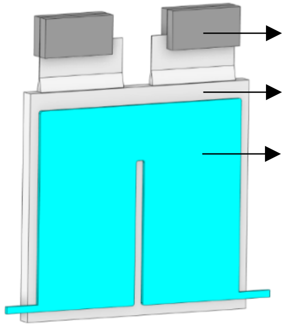
### Fluid conditions

- Material: Dielectric fluid
- Temperature: 25 °C
- Flowrate: 0.4 L/min

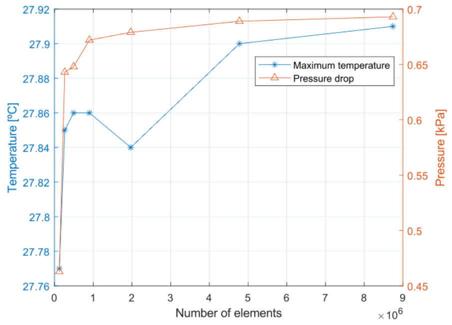
### Heat generation model

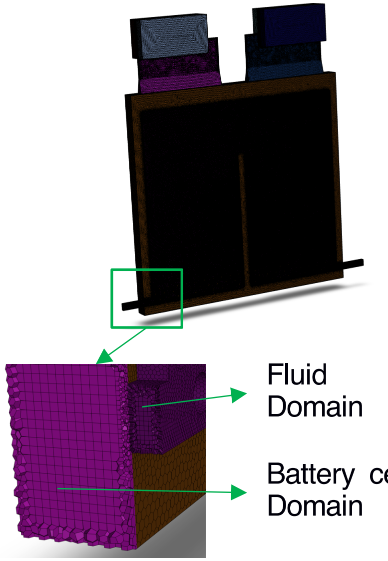
- 1C Discharge/Dischrage
- 1C Pulse tests




Battery cell equivalent model

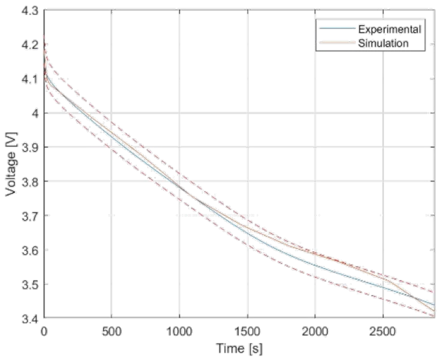


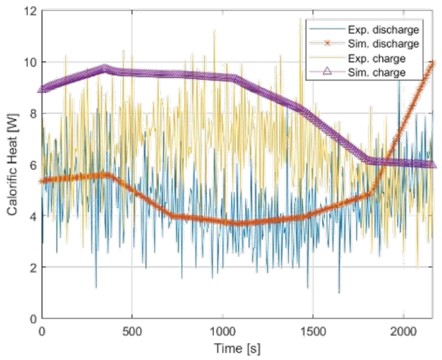

- Element number: 4778025
- Element size: 0.4mm
- Skewness av.: 0.07
- Min. orthogonal quality: 0.2 (0.9av)
- Objective: Error less than 1%

Mesh independence test

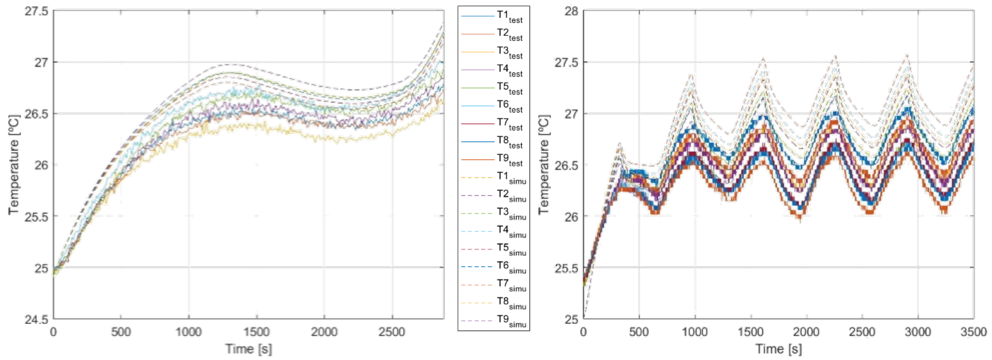
Voltage validation




Heat generation validation




Transient temperature validation




Simulation model validation V, T, Q

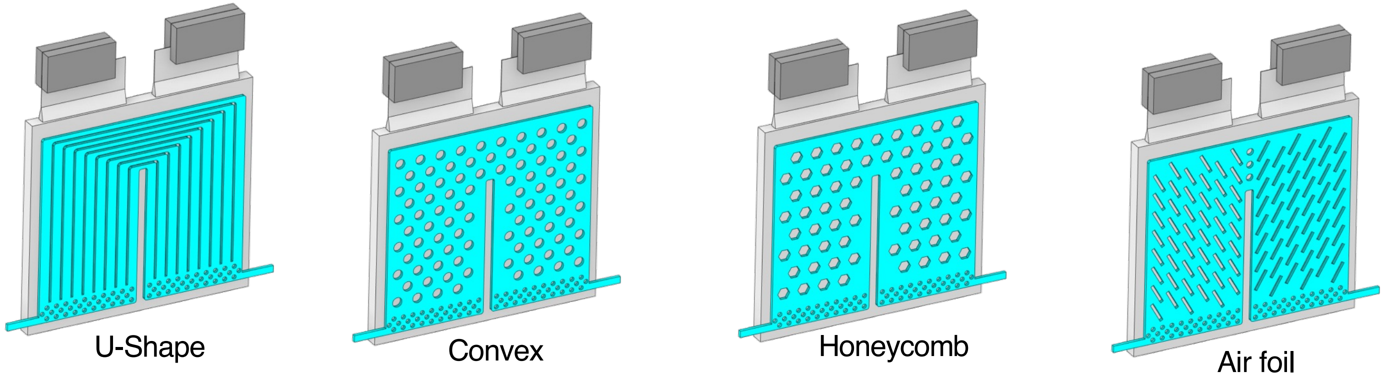
# Optimization process and results

## Flow pattern design selection

Objective:

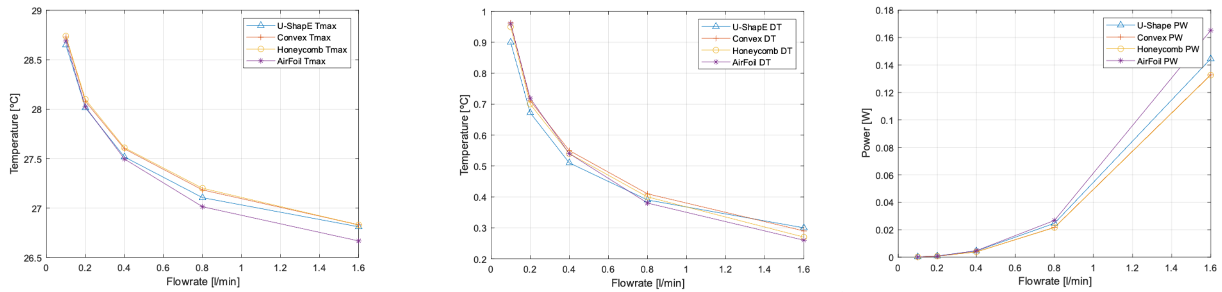
Analyse the flow patter design influence on the cooling performance of the strategy.

- Same fluid-cell contact área: 26400 $mm^2$
- Same working conditions

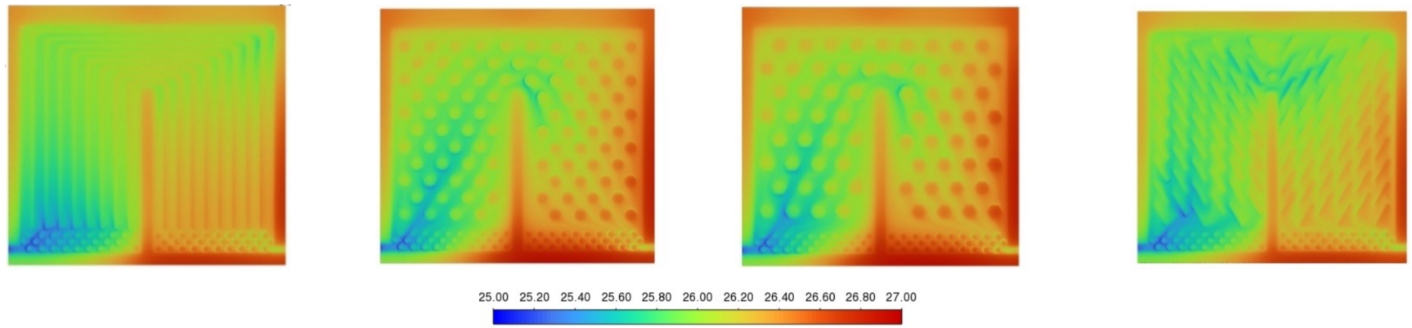



Parameters to analyse

- $\Delta P$ — Power consumption
- $T_{max}$
- $\Delta T$ — Thermal performance



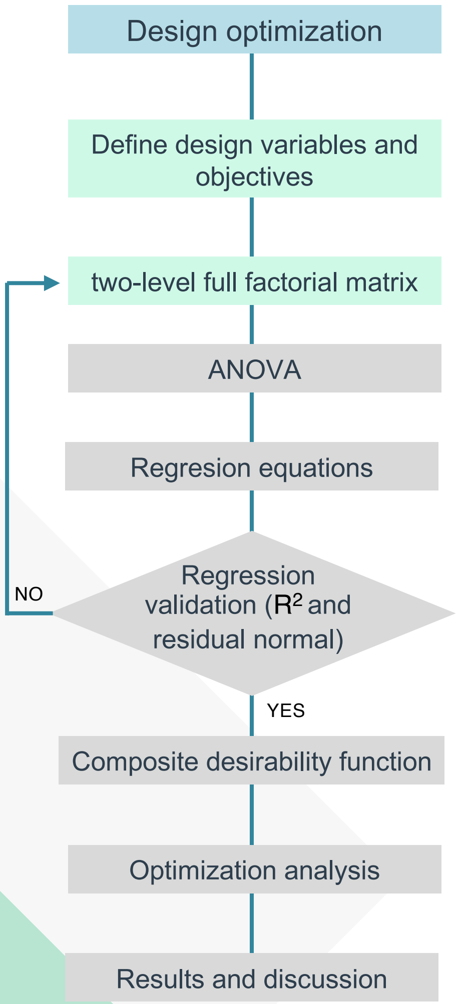

| 0.4 l/min | U-Shape | Convex | Honeycomb | Air Foil |
|---|---|---|---|---|
| $\Delta P$ | Medium | Lowest | Medium | Highest |
| $T_{max}$ | Lowest | Highest | Medium | Medium |
| $\Delta T$ | Lowest | Highest | Medium | Medium |

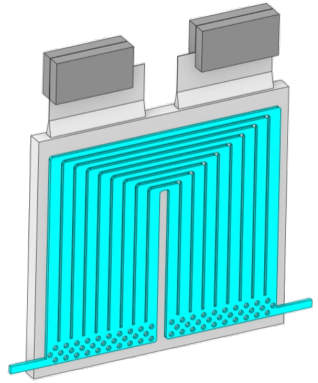


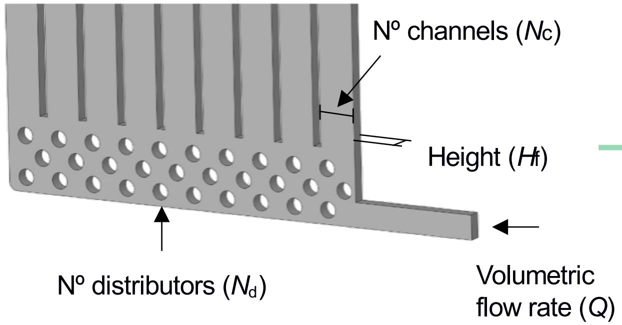

Thermal picture of each flow pattern design in the thermal stabilization section

# Optimization process and results

## Design optimization – Full factorial matrix definition



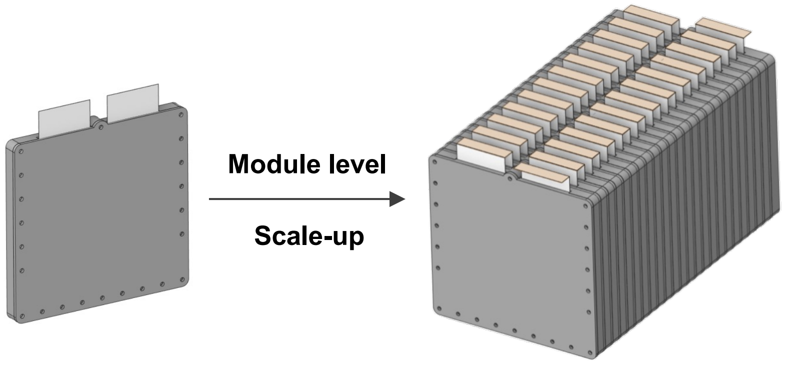






| | |
|---|---|
| $H_f$ (mm) | 1 - 3 |
| $N_c$ | 3 - 9 |
| $N_d$ | 10 - 30 |
| $Q$ (l/min) | 0.13 – 0.4 |

- 4 parameters
- Two levels of study
- Full factorial analysis

$2^4$ simulation




**Cell level** — Battery cell → **Results Scale-up** → **System level** — Battery module with 24 battery cells

**Thermal performance** ($T_{max}$, $\Delta T$)

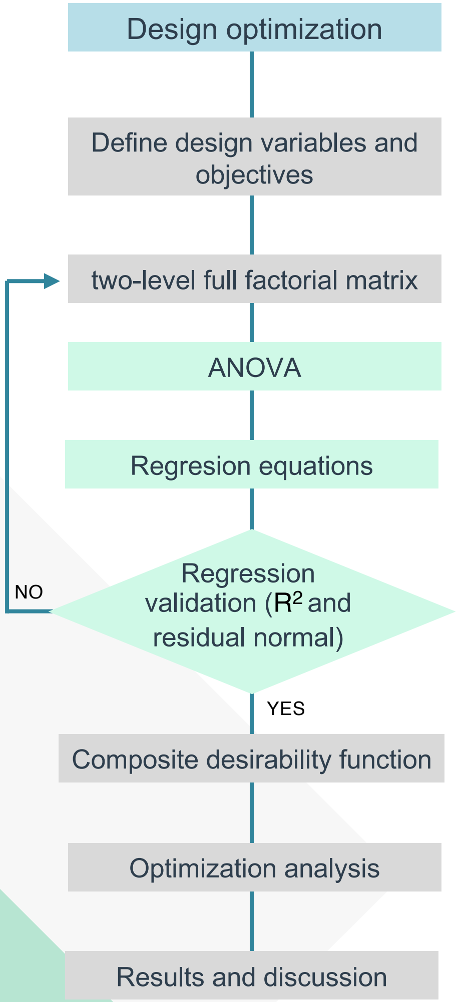
**Energy and Consumption** ($VED$, $P_h$)

| **4 input** parameters | **4 output** objective variables |
|---|---|
| Height of the fluid channel – $H_f$ | $T_{max}$ – Cell |
| Number of channels– $N_c$ | $\Delta T$ – Cell temperature heterogeneity |
| Number of distributors– $N_d$ | $VED$ – Module volumetric energy density |
| Volumetric flowrate– $Q$ | $P_h$ – Module pumping power consumption |

| Nº simulations | $H_f$ (mm) | $N_c$ | $N_d$ | $Q$ (l/min) | Cell level | | Module level | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $T_{max}$ (ºC) | $\Delta T$ (ºC) | $VED$ (Wh/L) | $P_h$ (W) |
| 1 | 3 | 9 | 30 | 0.4 | 27.52 | 0.51 | 248.70 | 0.1089 |
| 2 | 1 | 9 | 30 | 0.4 | 27 | 0.37 | 279.78 | 1.455 |
| 3 | 3 | 3 | 30 | 0.4 | 27.51 | 0.56 | 248.70 | 0.0948 |
| 4 | 1 | 3 | 30 | 0.4 | 26.98 | 0.38 | 279.78 | 1.301 |
| 5 | 3 | 9 | 10 | 0.4 | 27.56 | 0.47 | 248.70 | 0.0764 |
| 6 | 1 | 9 | 10 | 0.4 | 27.02 | 0.35 | 279.78 | 1.162 |
| 7 | 3 | 3 | 10 | 0.4 | 27.51 | 0.49 | 248.70 | 0.069 |
| 8 | 1 | 3 | 10 | 0.4 | 26.98 | 0.36 | 279.78 | 1.06 |
| 9 | 3 | 9 | 30 | 0.13 | 28.36 | 0.78 | 248.70 | 0.0086 |
| 10 | 1 | 9 | 30 | 0.13 | 27.73 | 0.68 | 279.78 | 0.131 |
| 11 | 3 | 3 | 30 | 0.13 | 28.31 | 0.84 | 248.70 | 0.0073 |
| 12 | 1 | 3 | 30 | 0.13 | 27.7 | 0.71 | 279.78 | 0.118 |
| 13 | 3 | 9 | 10 | 0.13 | 28.37 | 0.73 | 248.70 | 0.0065 |
| 14 | 1 | 9 | 10 | 0.13 | 27.72 | 0.65 | 279.78 | 0.115 |
| 15 | 3 | 3 | 10 | 0.13 | 28.27 | 0.76 | 248.70 | 0.0056 |
| 16 | 1 | 3 | 10 | 0.13 | 27.69 | 0.67 | 279.78 | 0.1035 |

# Optimization process and results

## Design optimization – Optimization process validation




### ANOVA

$T_{max}$= 27.6+ 0.28$H_f$ -0.38 $Q$

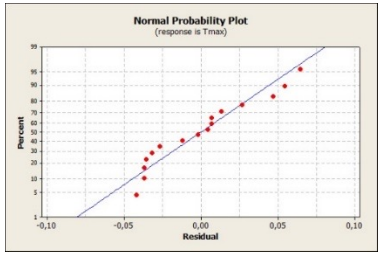
$\Delta T$= 0.58+ 0.06$H_f$ -0.014$N_c$ + 0.022$N_d$-0.146 $Q$ + 0.008$H_f$ $N_d$+ 0.01$H_f$ $Q$

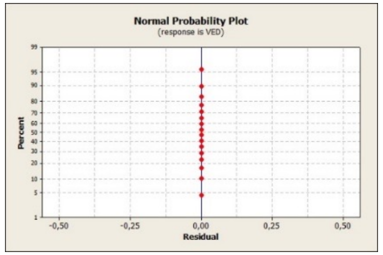
$VED$ = 264.24-15.54$H_f$

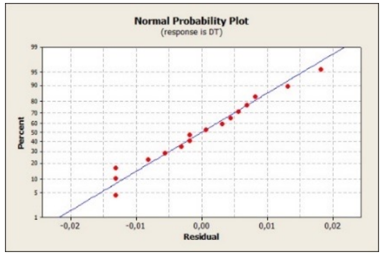
$P_h$ = 0.364-0.316$H_f$ + 0.039$N_d$ + 0.302 $Q$ -0.031 $H_f$ $N_d$ -0.261$H_f$ $Q$ + 0.035$N_d$ $Q$

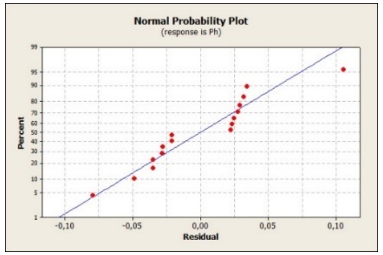
- Significance level below 0.05
- $H_f$ and $Q$ the most relevant factors
- $VED$ only influenced by $H_f$ (No variability)
- $N_c$ and $N_d$ influence on $\Delta T$ and $P_h$

### Regression model validation ($R^2$ and residuals)




| | $R^2$ (Adequate) | $R^2$ (Predicted) | $R^2$ (Adjusted) |
|---|---|---|---|
| $T_{max}$ | 90% | 85% | 89% |
| $\Delta T$ | 99% | 99% | 99% |
| $VED$ | 100 % | 100 % | 100 % |
| $P_h$ | 99% | 98% | 99% |

The quality and the correlation of the $R^2$ indicators and the residuals of each response demonstrates the reliability of the regression models.

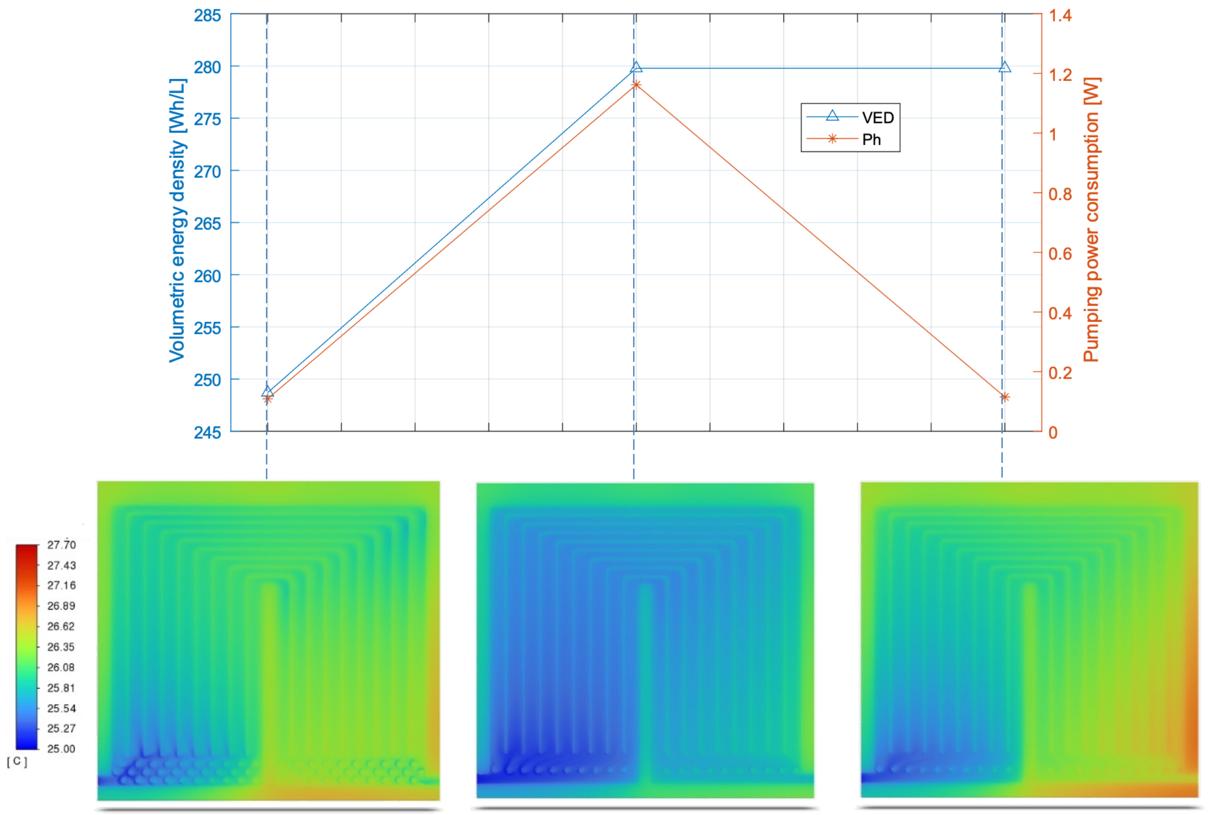
# Optimization process and results

## Design optimization – Results and analysis

- Design optimization
- Define design variables and objectives
- two-level full factorial matrix
- ANOVA
- Regresion equations
- Regression validation ($R^2$ and residual normal) — NO: back to two-level full factorial matrix; YES: continue
- Composite desirability function
- Optimization analysis
- Results and discussion

**Composite desirability function**

- Thermal approach
  - Maximize the thermal performance — ($T_{max}$, $\Delta T$)
- Feasibility approach
  - Maximize the thermal performance
  - Minimum power loss
  - Maximum energy density
  - ($T_{max}$, $\Delta T$, *VED*, $P_h$)




Reference model
$H_f$ = 3mm, $N_c$ = 9,
$N_d$ = 30, and $Q$ = 0.4 l/min

Maximum thermal performance
$H_f$ = 1mm, $N_c$ = 9,
$N_d$ = 10, and $Q$ = 0.4 l/min

Maximum global performance
$H_f$ = 1mm, $N_c$ = 9,
$N_d$ = 10, and $Q$ = 0.13 l/min

- Lower pressure drop ↓ $P_h$
- Higher volumetric energy density ↑ *VED*
- Thermal response control
- Higher applicability
- Higher efficiency

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## Contents

- General overview
- Optimization process and results
- **Concluding statements and future lines**

# Concluding statements and future lines

## Conclusions

**Optimization process results**

- U-Shape design — Best thermal performance of the battery cell without increasing the power consumption impact on the system.
- Most critical parameters — Height of the fluid channel ($H_f$) and the flowrate definition ($Q$), which are directly related to the fluid velocity.
- The number of channels ($N_c$) — Increases the power consumption of the system ($P_h$) while decreasing the thermal heterogeneity of the battery cell ($\Delta T$).
- The number of distributors ($N_d$) — Increases the power consumption of the system ($P_h$) and the thermal heterogeneity of the battery cell ($\Delta T$).

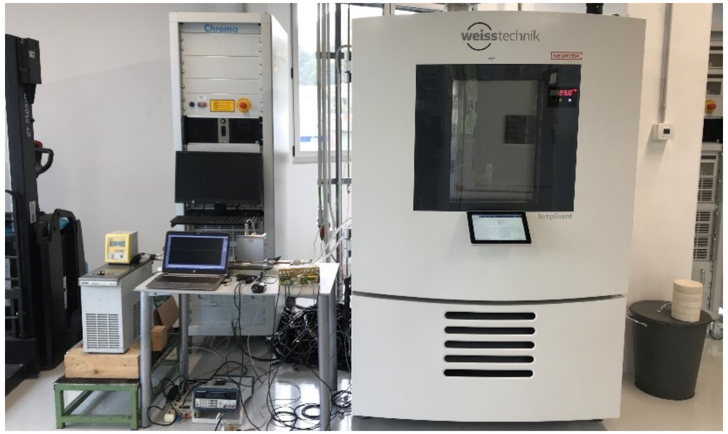
**General overview**

- Proposed Partial Direct Liquid Cooling strategy — More accurate thermal management control without the need to increase the power consumption of the auxiliary system.

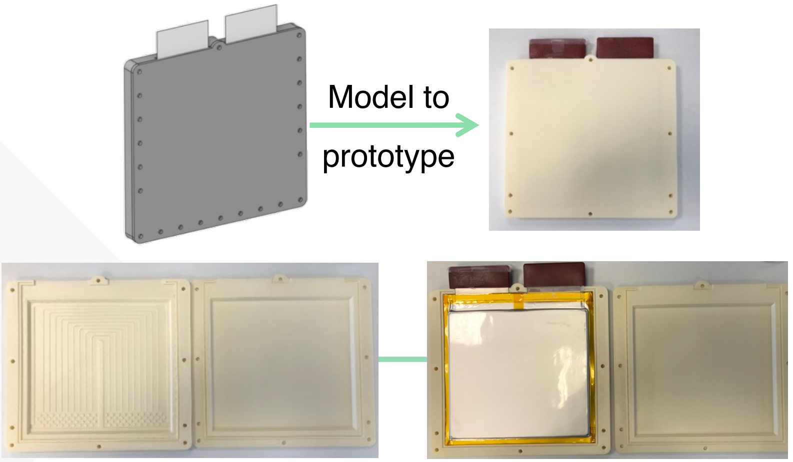
# Concluding statements and future lines

## Future lines

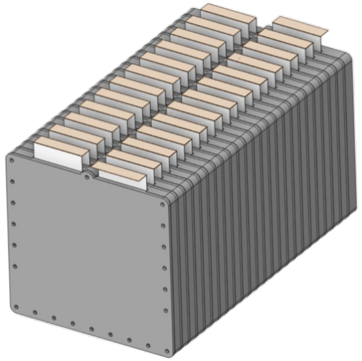
- Implement the optimization design on the prototype model
- Develop a prototype of 24 cells using additive manufacturing
- Define testing inputs based on the pumping power consumption criterion
- Develop the testing process
- Compare the proposed optimized DLC strategy with the ILC strategy in a module level



Fully experimental testing process

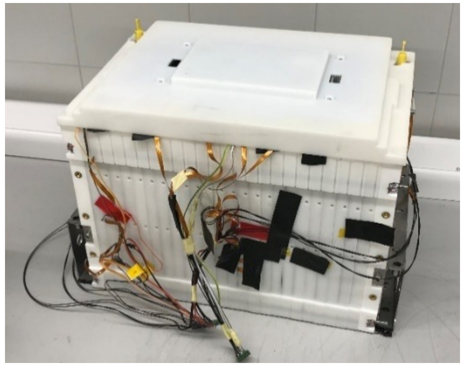



Numerically optimized design prototyping



Direct Liquid Cooling (DLC)

VS



Indirect Liquid Cooling (ILC)





# Thank you!

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