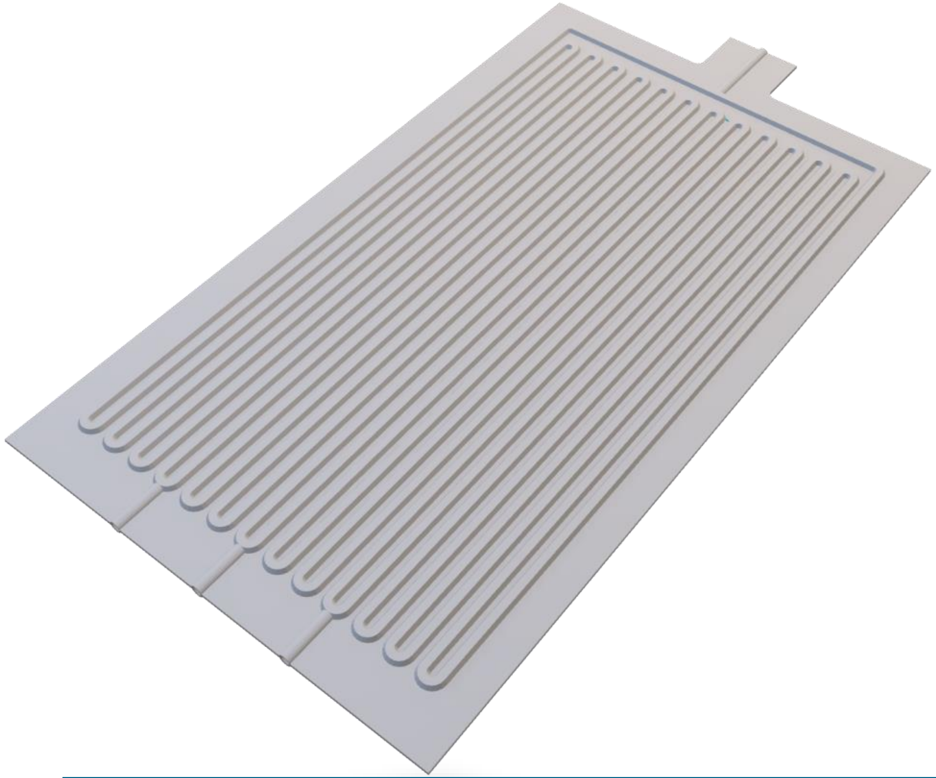
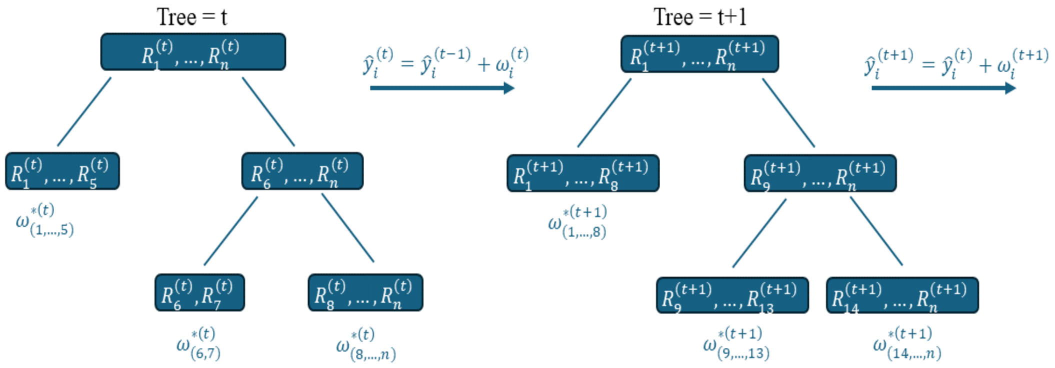
Towards Pulsating Heat Pipe Performance Prediction



Friedrich Franke, Marvin Illbruck, Markus Kober, Lars Enghardt, Stefan Kazula | DLR | Stuttgart 2026

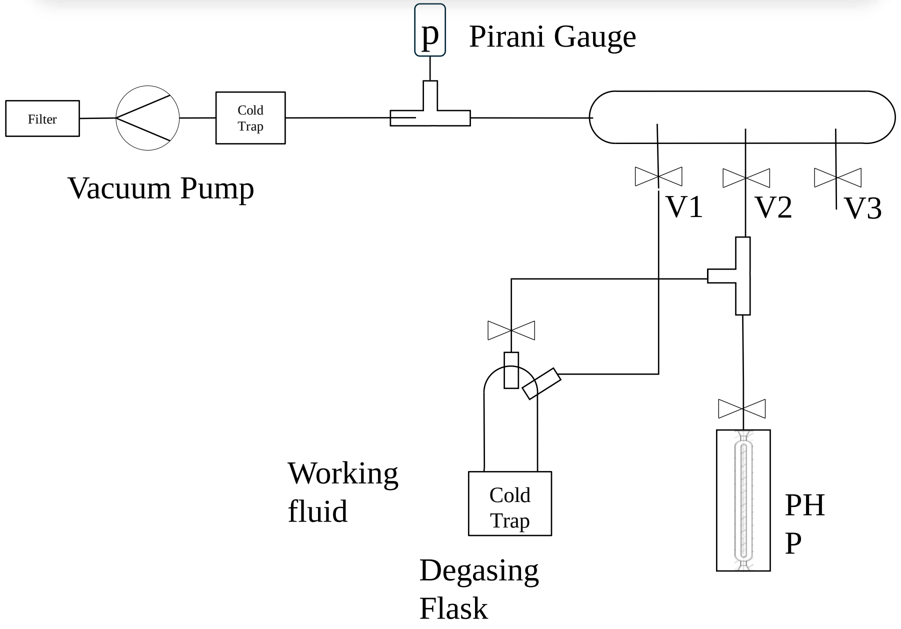
Towards Pulsating Heat Pipe Performance Prediction

Gradient Boosting



&

Experimental Iteration



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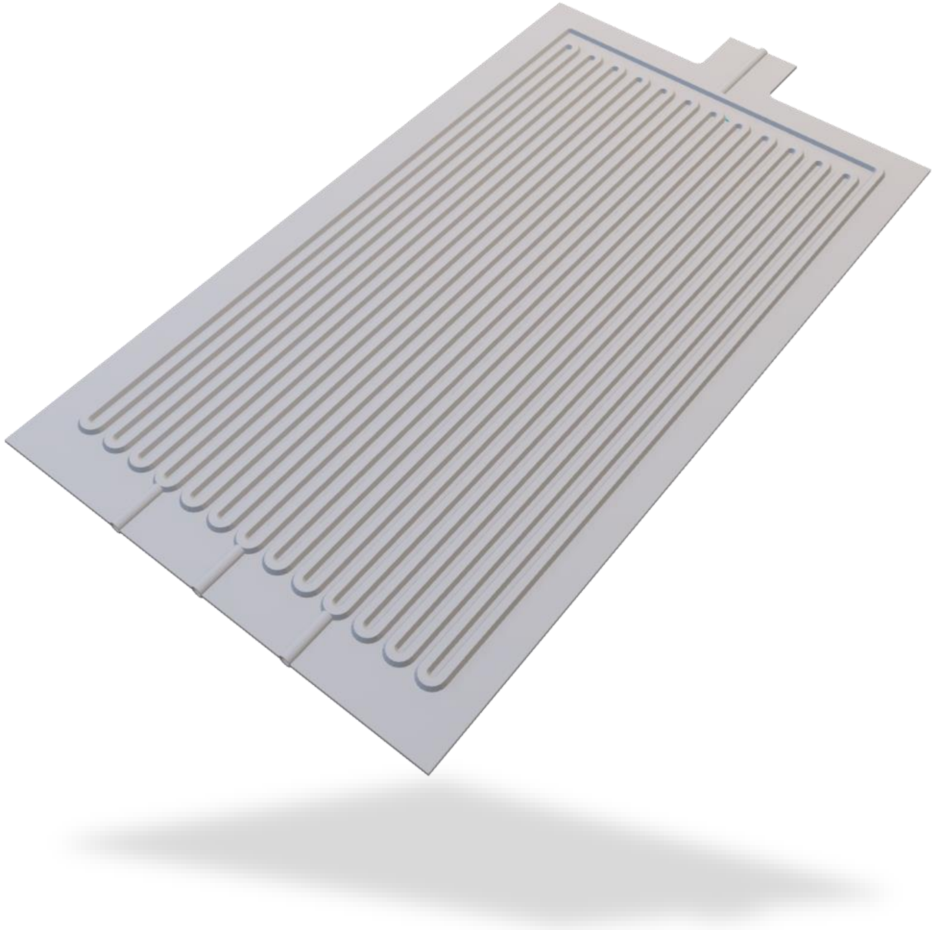
Pulsating Heat Pipe (PHP)



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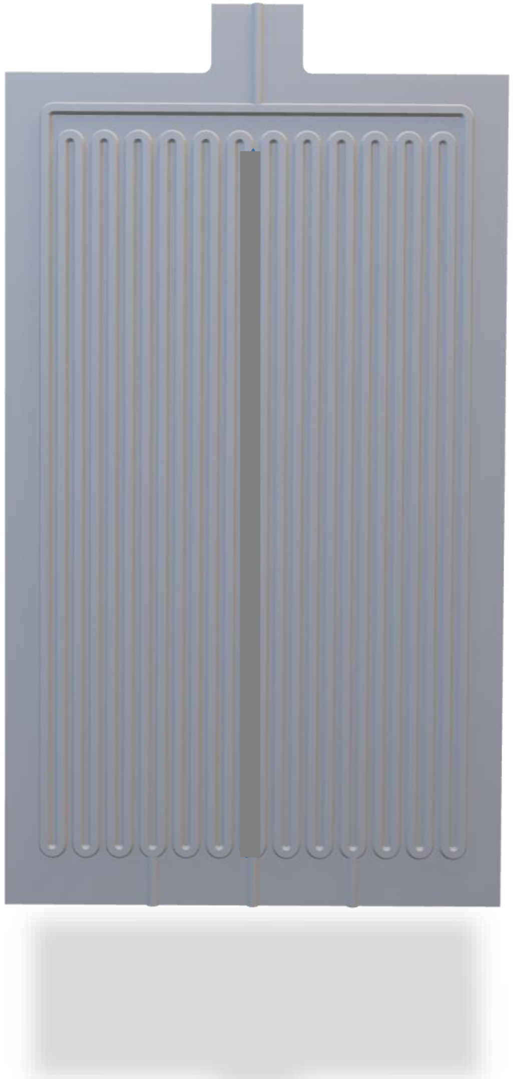
Pulsating Heat Pipe (PHP)



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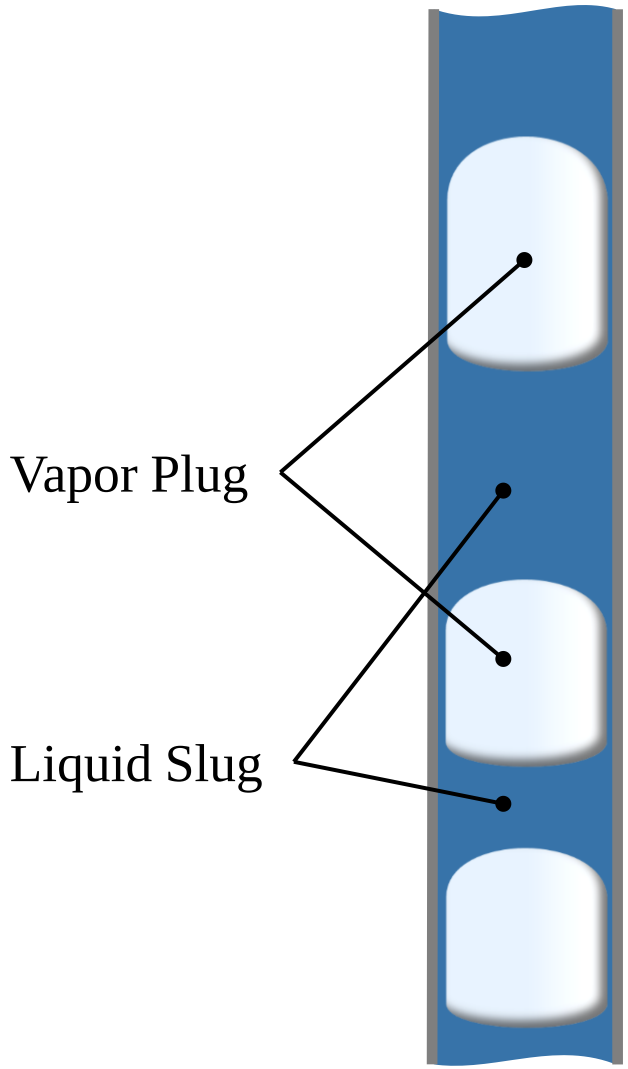
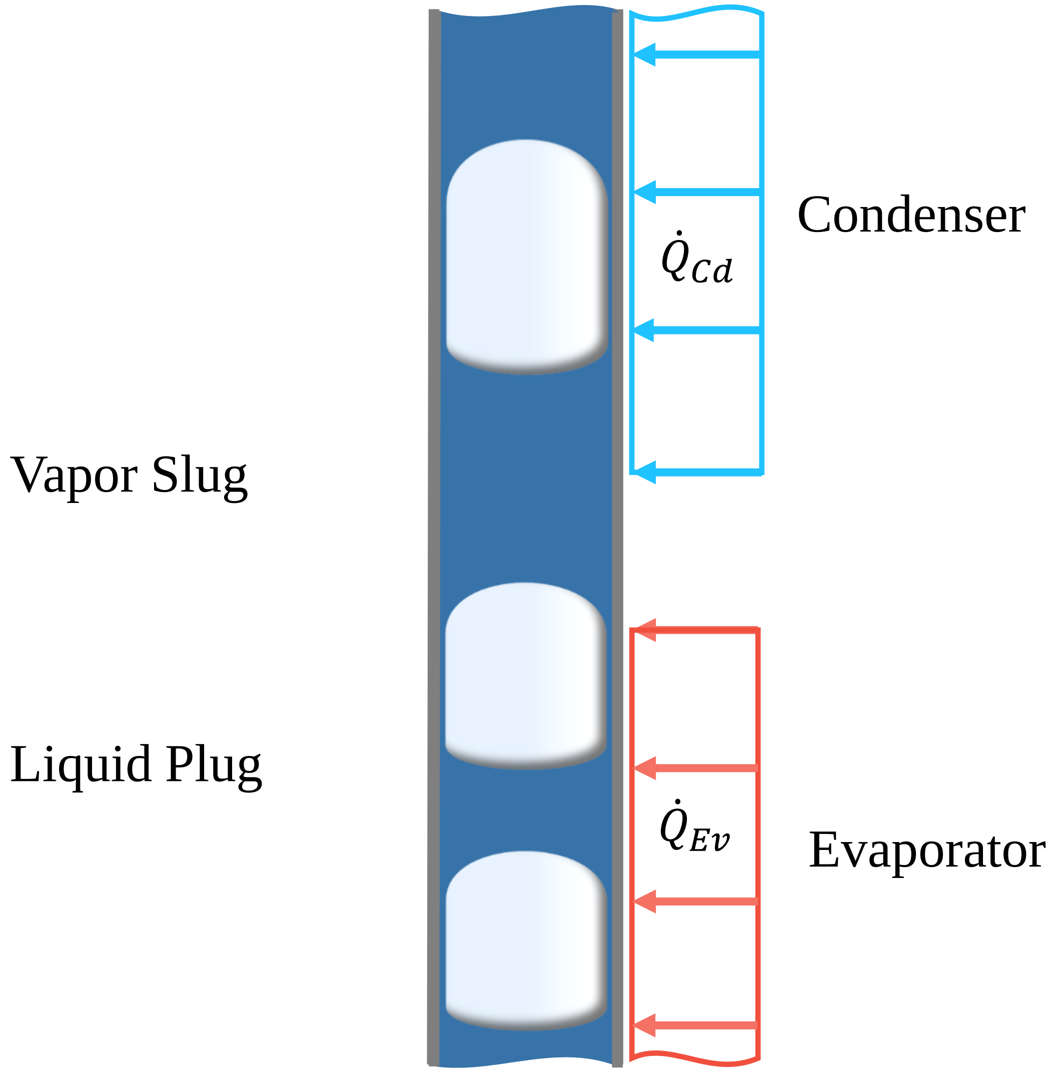
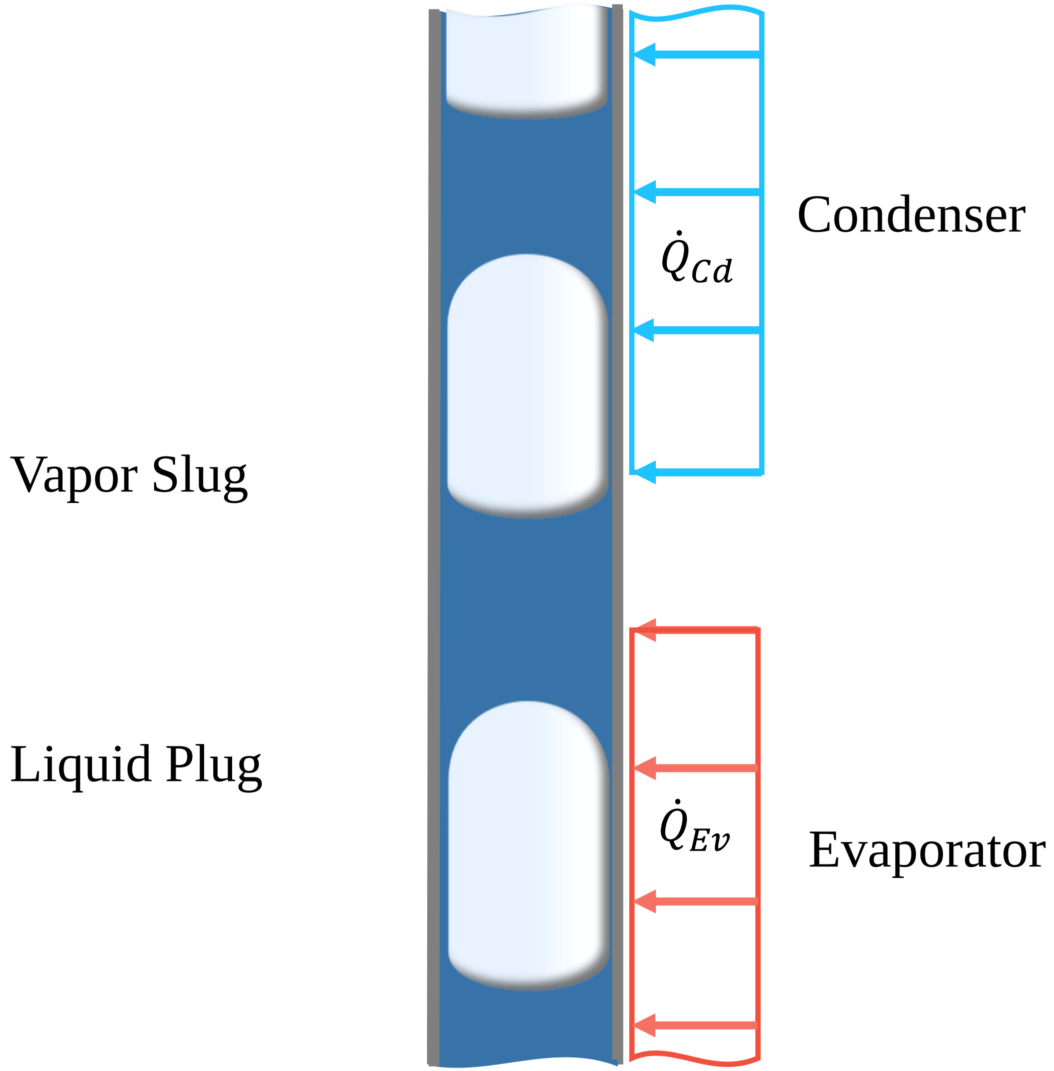
PHP Working Principle



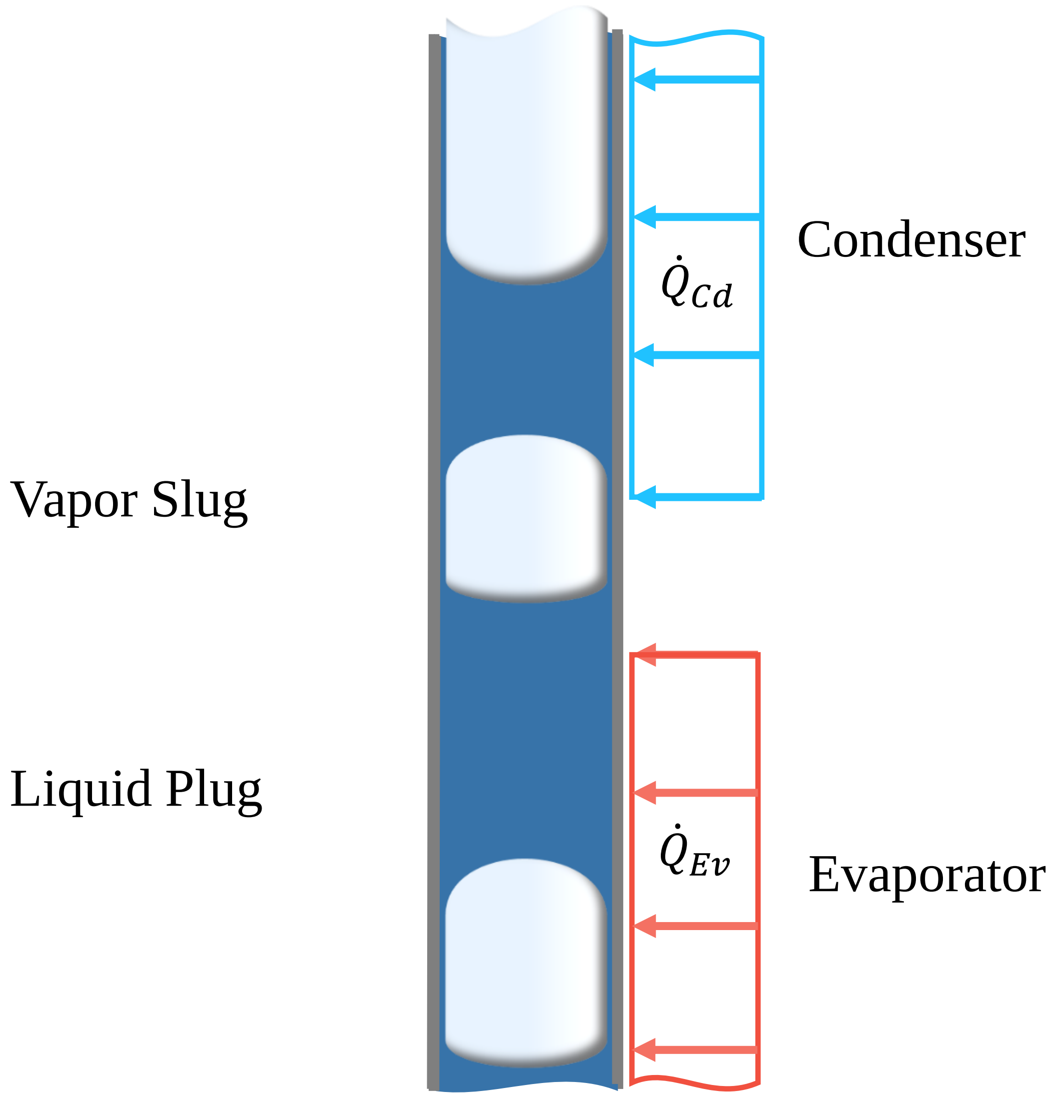
PHP Working Principle



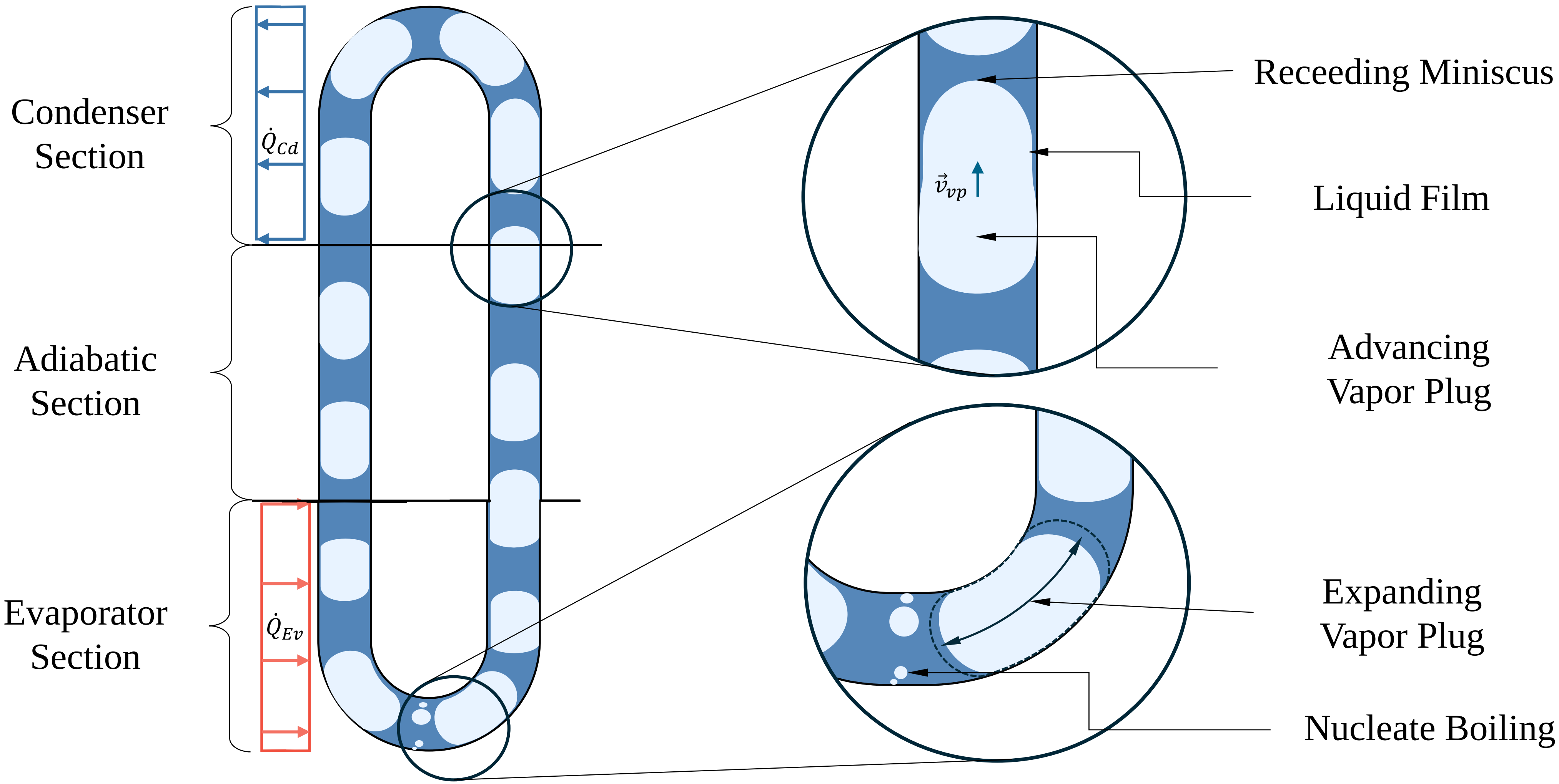
PHP Working Principle



PHP Working Principle

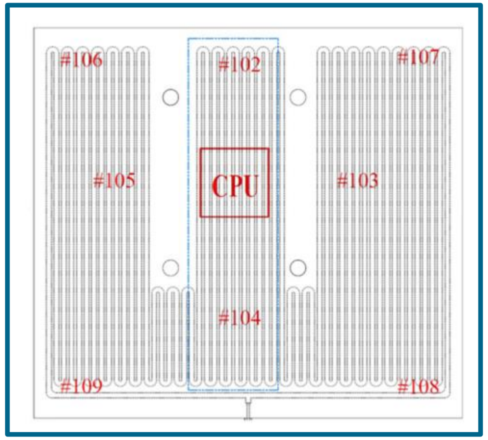


PHP Working Principle

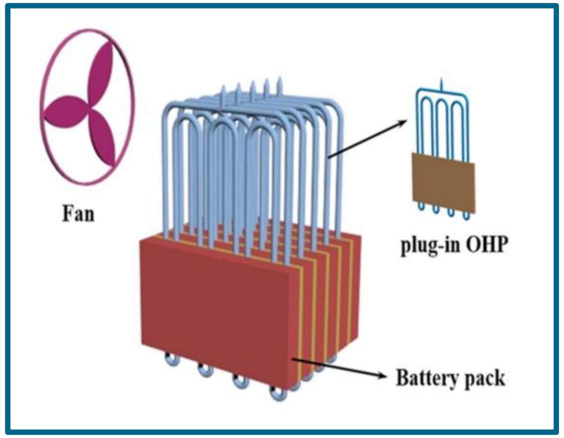


State of Research

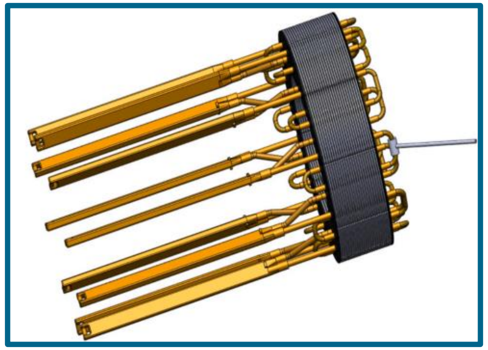
- **Applications**
  - CPU cooling, *[Li 2023]*
  - Battery cooling *[Wei 2019]*
  - Electric machines *[Aziza 2025]*
  - Fuel cell cooling



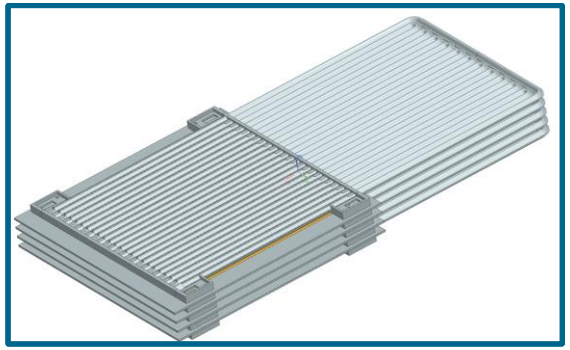
CPU Cooling *[Li 2023]*



Battery Pack Cooling *[Wei 2019]*



Electric Machine *[Aziza 2025]*

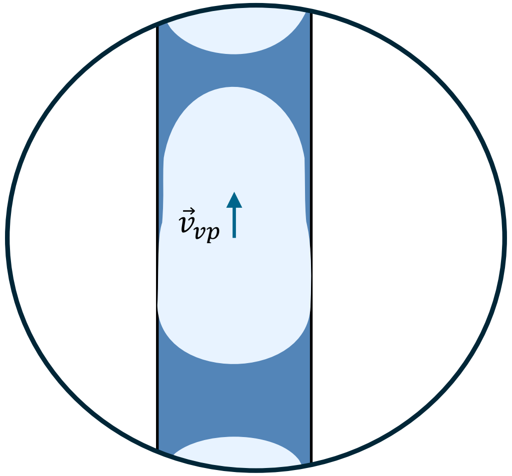


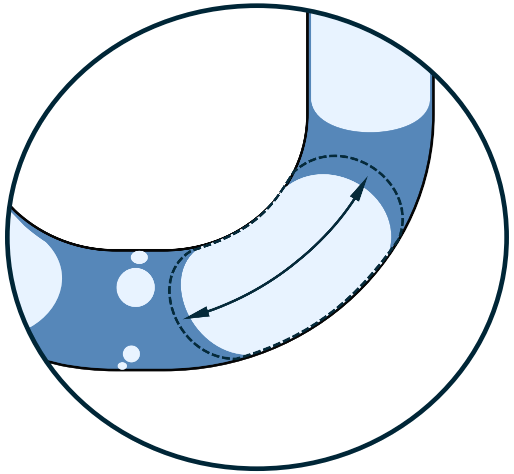
Fuel Cells *[Franke 2025]*

State of Research

- **Applications**
  - CPU *[Li 2023]*, Battery *[Wei 2019]*
  - Electric machines *[Aziza 2025]*, *Fuel Cells*

- **Simulation**
  - Complex multiphase & capillary interactions
  - transient nature and long start up times *[Fang 2024]*
  - *CFD lacks predictive capability*
  - *1D-abstraction: some successes [Nikolayev 2021]*





State of Research

- **Applications**
  - CPU *[Li 2023]*, Battery *[Wei 2019]*
  - Electric machines *[Aziza 2025], Fuel Cells*
- **Simulation**
  - Complex multiphase & capillary interactions
  - transient nature and long start up times *[Fang 2024]*
  - *CFD lacks predictive capability*
  - *1D-abstraction: some successes [Nikolayev 2021]*

2 Phase problem

Small scale capillary forces

Wall friction & wetting

Unclear vapour state

Boiling, condensing & evaporation

Film deposition mechanics

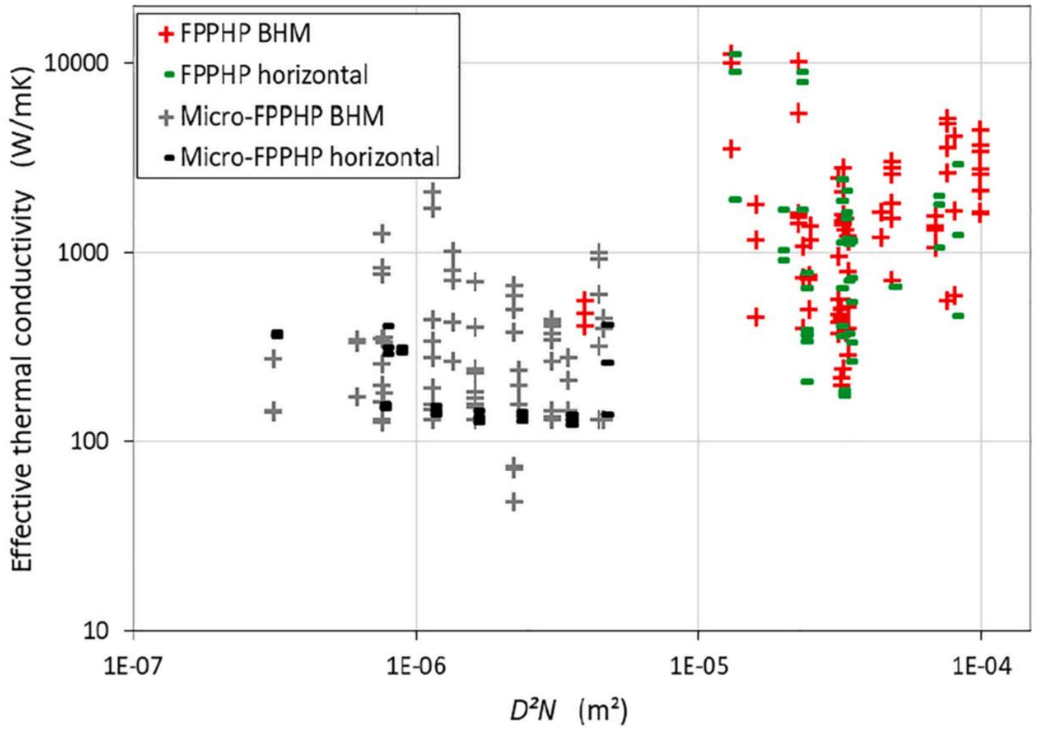
Dynamic and long start up time

State of Research

- **Applications**
  - CPU *[Li 2023]*, Battery *[Wei 2019]*
  - Electric machines *[Aziza 2025], Fuel Cells*

- **Simulation**
  - Comple, Transient *[Fang 2024]*
  - *CFD lacks predictive capability*
  - *1D-abstraction: [Nikolayev 2021]*

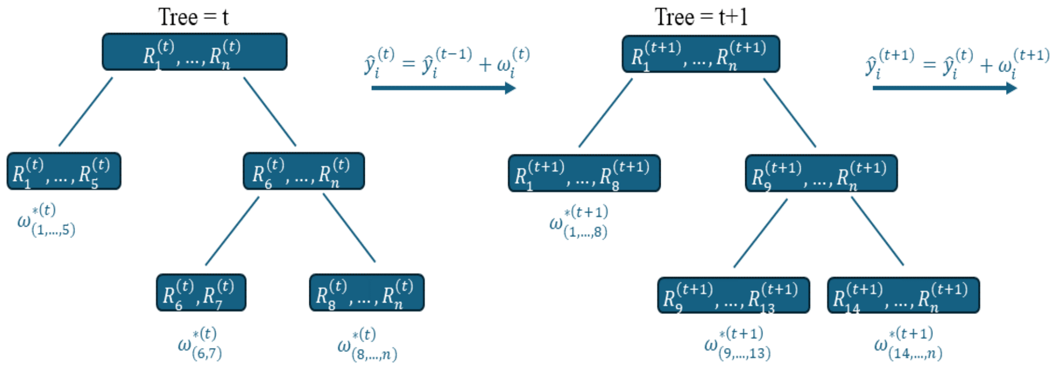
- **Experimentation**
  - Large variation in measured thermal performances *[Ayel 2021]*
  - Variations in experimental setup



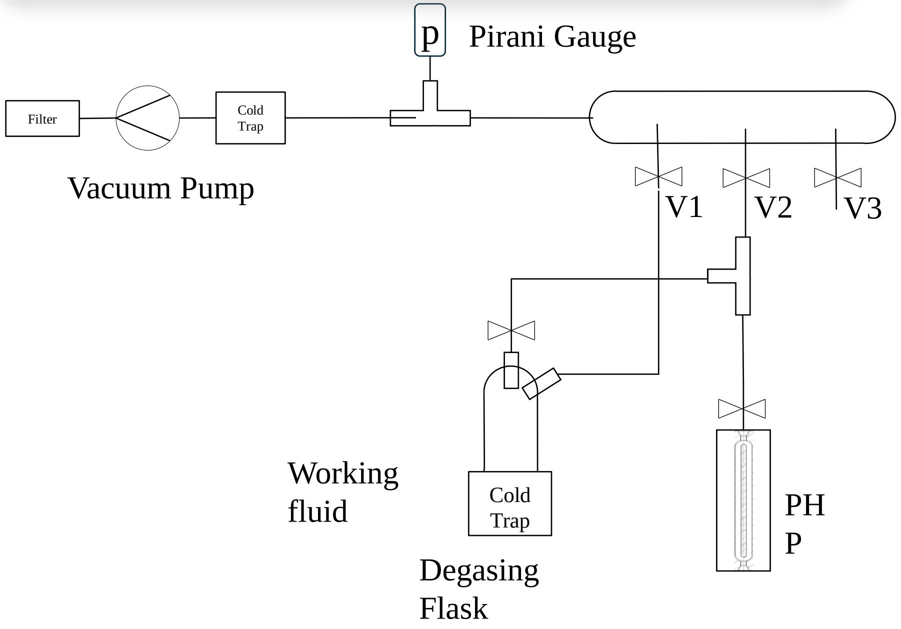
Equivalent thermal conductivities; *data from [Ayel 2021]*

Dual Approach of this Work

Thermal Resistance Prediction With Gradient Boosting

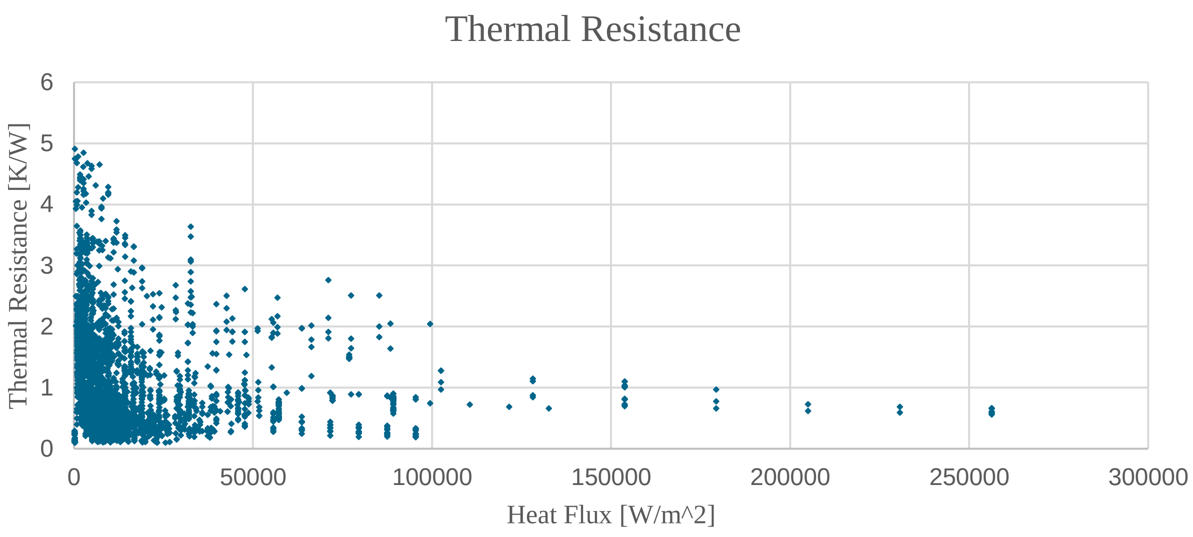


Setup for Design of Experiments



Thermal Resistance Prediction With Gradient Boosting

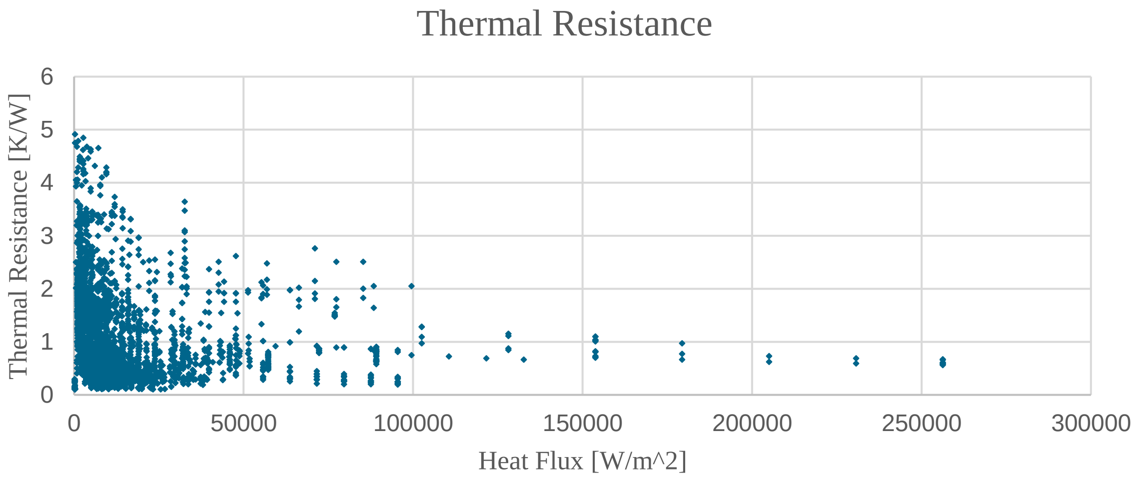
- **Collecting & curating PHP data**
  - 3441 Cases from Literature *[ref. in Appendix]*

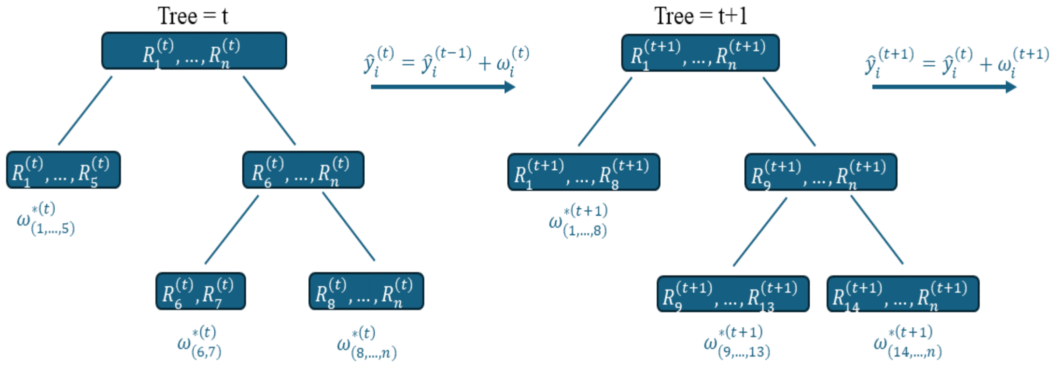


Visualization of the XG Boost Algorithm

Thermal Resistance Prediction With Gradient Boosting

- Collecting & curating PHP data
  - 3441 Cases from Literature *[ref. in Appendix]*
- **Train a ML model** *[Illbruck 2026]*
- **Predict thermal performance**
  - $\boldsymbol{Key\ metric: Thermal\ resistance\ R_{th}}$
- Validate Prediction
  - Design of Experiments Setup





Visualization of the XG Boost Algorithm

Thermal Resistance Prediction With Gradient Boosting

- **Train a ML model** *[Illbruck 2026]*
  - *XG Boost Algorithm*
    [Friedman 2012, Chen 2016]

Case	Heat $[W]$	Pipe mat.	Fluid	$R_{th}\ [K/W]$
1	20	Copper	Water	1.00
2	40	Aluminium	Ethanol	0.85
3	60	Copper	Ethanol	0.60
4	80	Copper	Methanol	0.55
5	100	Aluminium	Water	0.20

Hypothetical, simplified PHP Data set

Thermal Resistance Prediction With Gradient Boosting

- **Train a ML model** *[Illbruck 2026]*
  - *XG Boost Algorithm*

    [Friedman 20012, Chen 2016]

Initial Guess: $\hat{y}^{(0)} = 1$

$\mathrm{r} = \hat{y}^{(0)} - y$

Case	Heat $[W]$	Pipe mat.	Fluid	$R_{th}\ [K/W]$	Residual r
1	20	Copper	Water	1.00	**0**
2	40	Aluminium	Ethanol	0.85	**0.15**
3	60	Copper	Ethanol	0.60	**0.4**
4	80	Copper	Methanol	0.55	**0.45**
5	100	Aluminium	Water	0.20	**0.8**

Hypothetical, simplified PHP Data set

Thermal Resistance Prediction With Gradient Boosting

Initial Guess

$\hat{y}^{(0)} = 1$

$\mathrm{r} = \hat{y}^{(0)} - y$

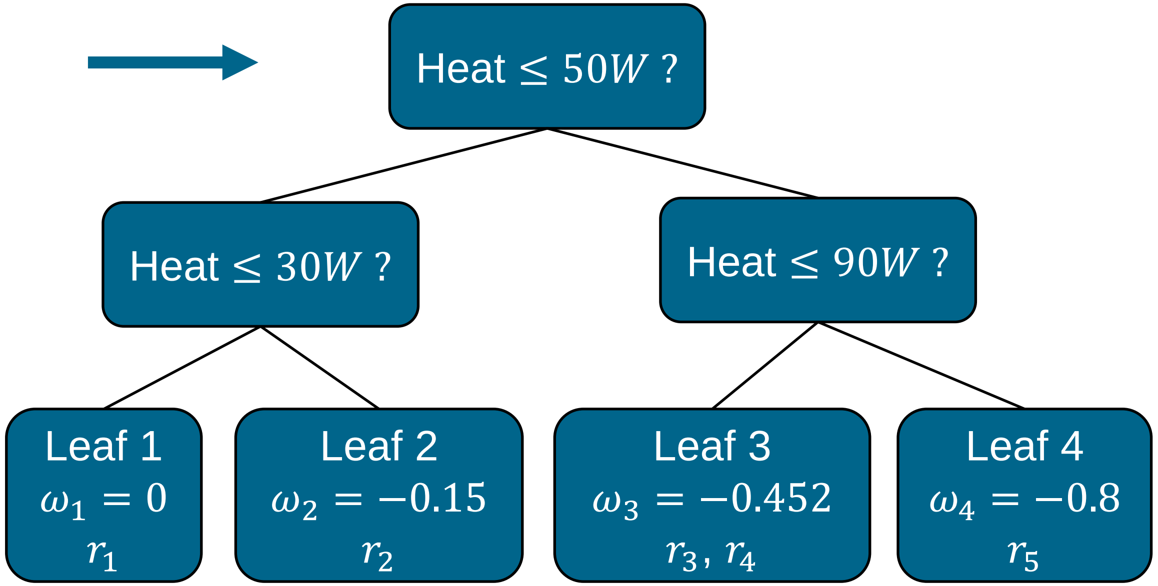
Thermal Resistance Prediction With Gradient Boosting

Initial Guess

$\hat{y}^{(0)} = 1$

$r = \hat{y}^{(0)} - y$

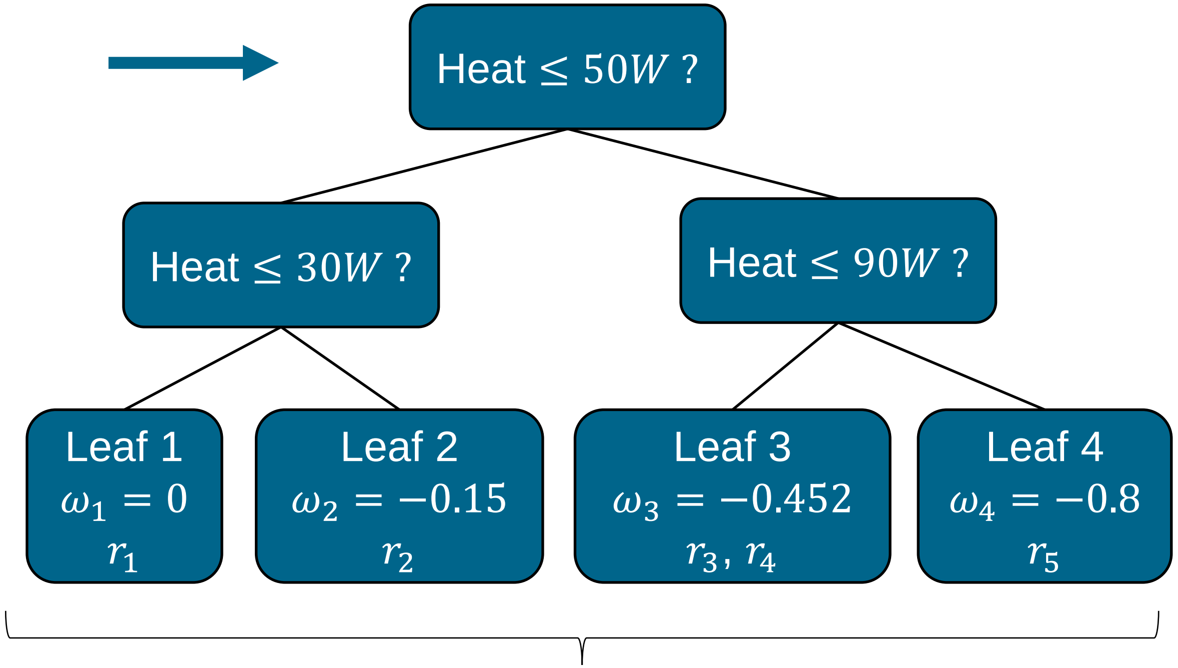
Tree $= t$



Clustering residuals and calculating weights ω_i

Thermal Resistance Prediction With Gradient Boosting

Tree = t



Clustering residuals and calculating weights ω_i

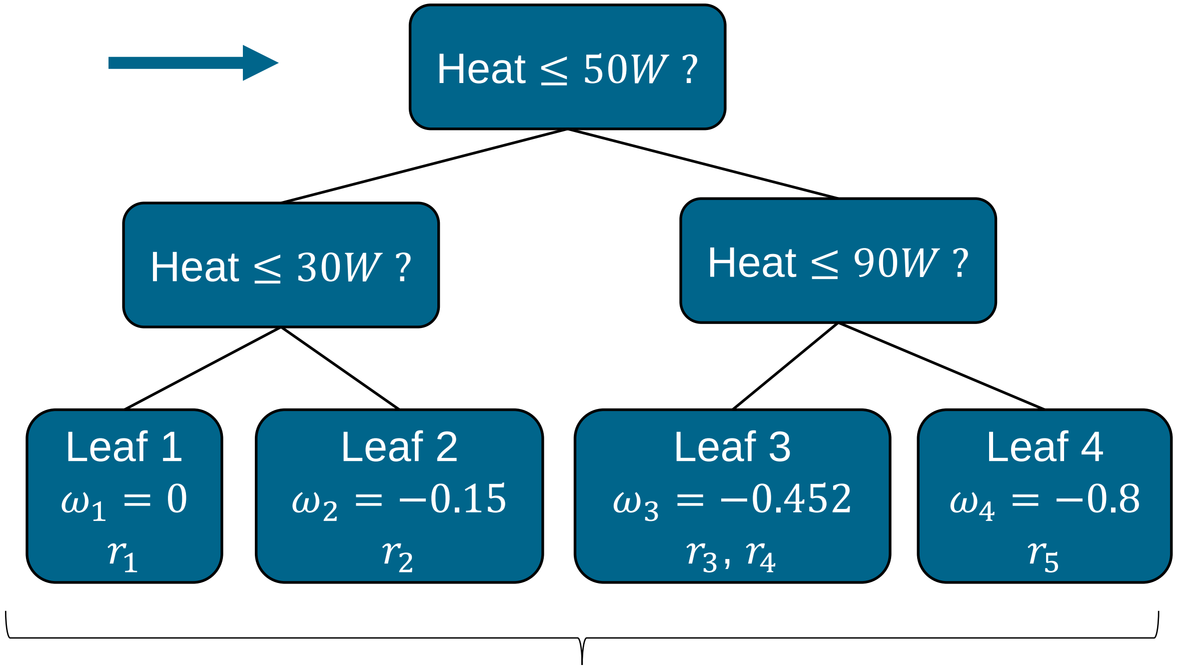
- ***Evaluation function***

$$L^{(t)} = \sum_{i=1}^{n} l\left(y_i, \hat{y}_i^{t-1} + f_t(x_i)\right) + \Omega(f_t)$$

  - *Regulization term* $\Omega(f_t) = \gamma T + \frac{1}{2}\lambda\|\omega^2\|$

Thermal Resistance Prediction With Gradient Boosting

Tree = t



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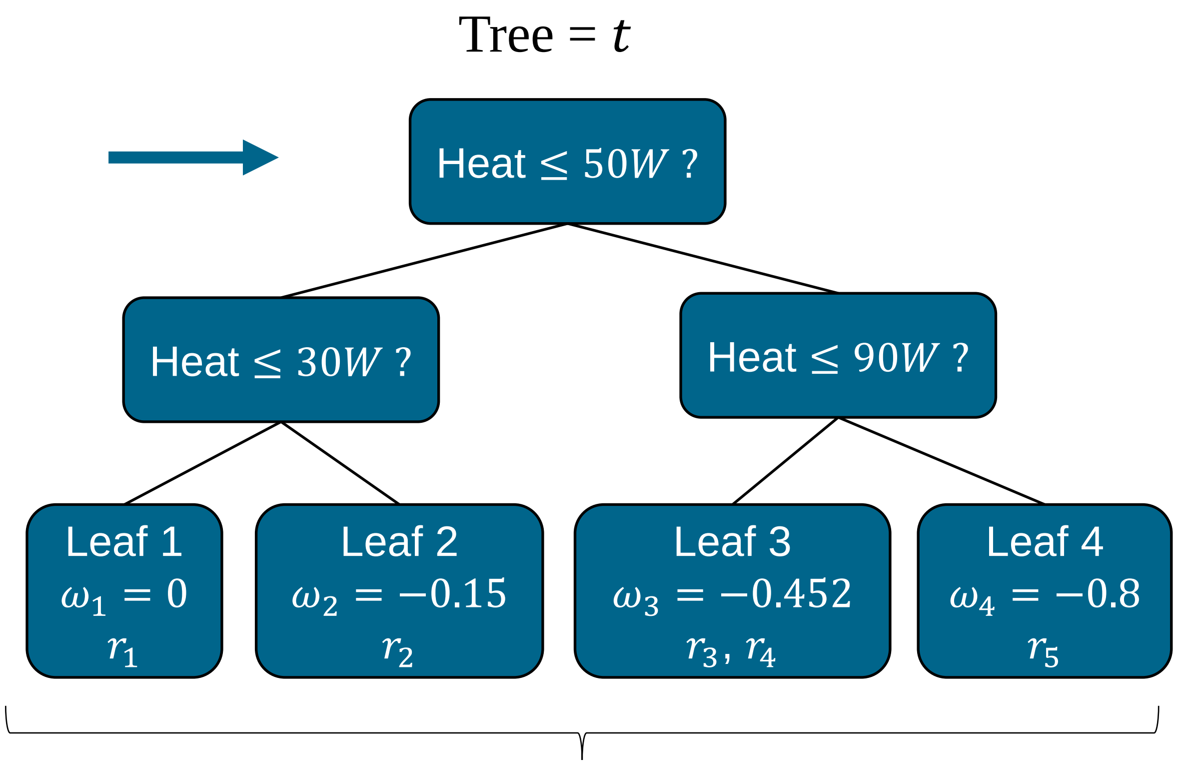
- **Taylor Approximation**

$$L^{(t)} \approx \sum_{i=1}^{n}\left[l(y_i, \hat{y}_i^{t-1}) + \frac{\partial\, l(y_i, \hat{y}_i^{t-1})}{\partial \hat{y}_i} f_t(x_i) + \frac{1}{2}\frac{\partial^2\, l(y_i, \hat{y}_i^{t-1})}{\partial {\hat{y}_i}^2} f_t(x_i)^2 + \mathcal{O}\right] + \Omega(f_t)$$

Thermal Resistance Prediction With Gradient Boosting



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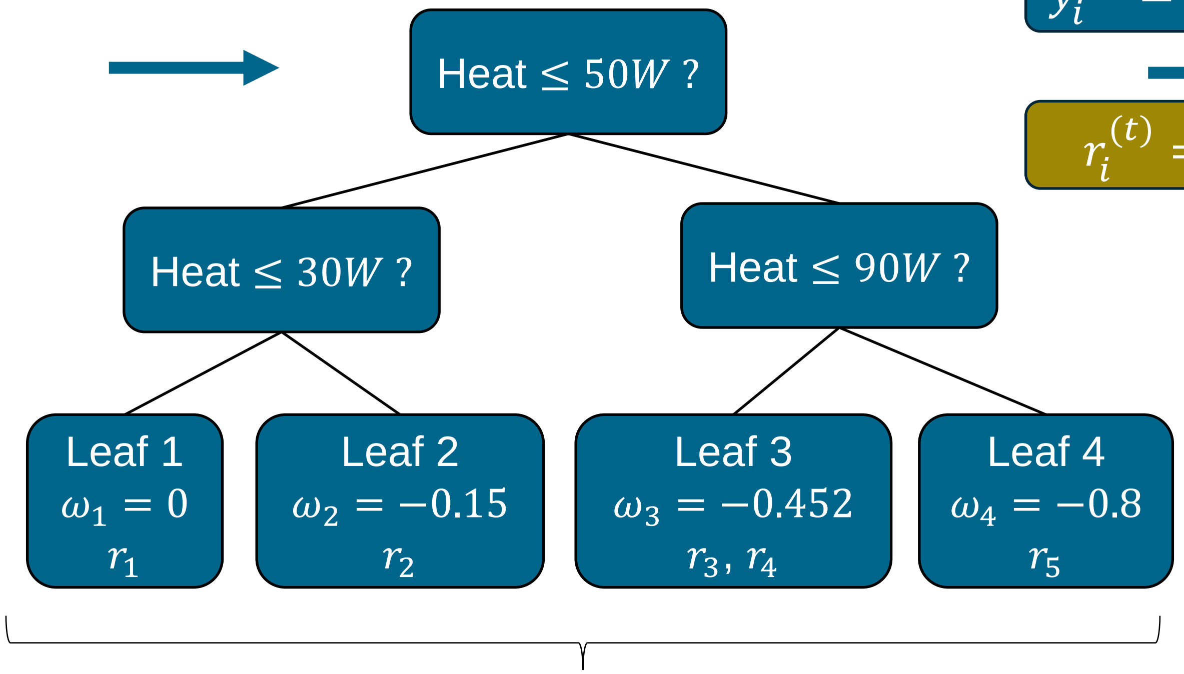
- **Gradient** $\frac{\partial L^{(t)}}{\partial f_t} = 0$

$$f_t(x_i) = \omega_j^* = -\frac{\sum_{i\epsilon I_j} \frac{\partial\, l\left(y_i, \hat{y}_i^{t-1}\right)}{\partial \hat{y}_i}}{\sum_{i\epsilon I_j} \frac{\partial^2\, l\left(y_i, \hat{y}_i^{t-1}\right)}{\partial \hat{y}_i{}^2} + \lambda}$$

Thermal Resistance Prediction With Gradient Boosting

Tree = t



Clustering residuals and calculating weights ω_i

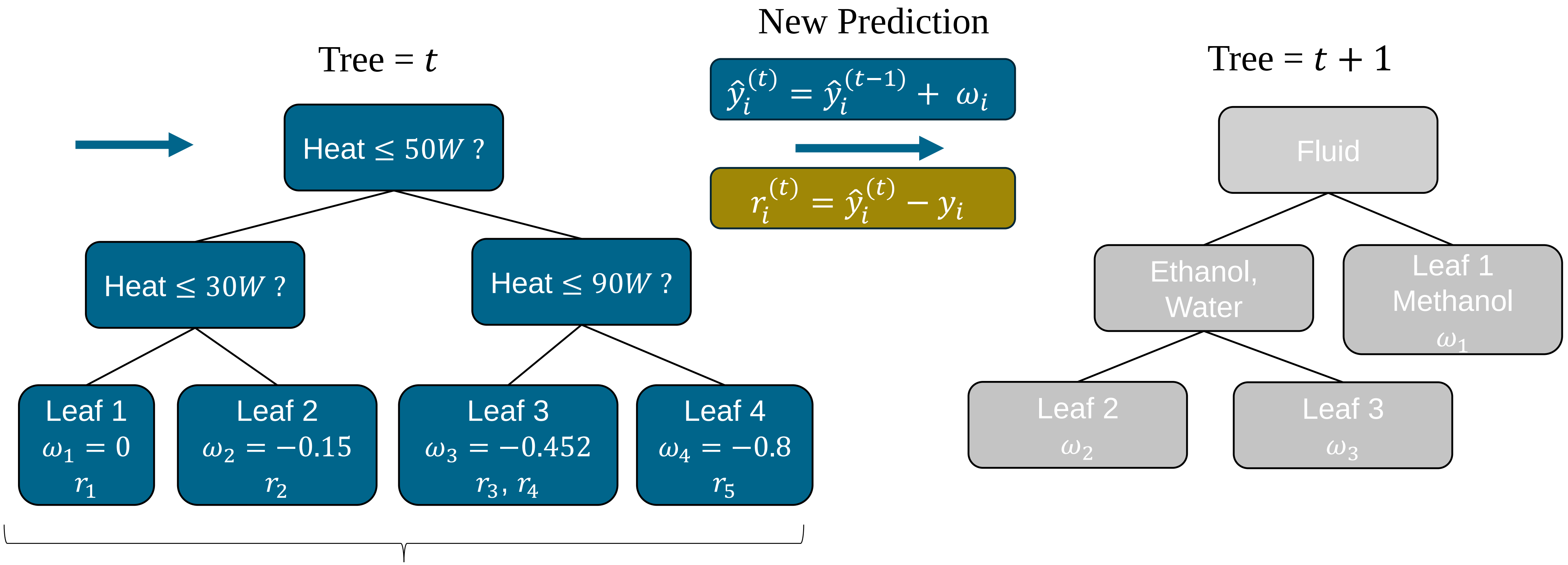
New Prediction

$$\hat{y}_i^{(t)} = \hat{y}_i^{(t-1)} + \omega_i$$

$$r_i^{(t)} = \hat{y}_i^{(t)} - y_i$$

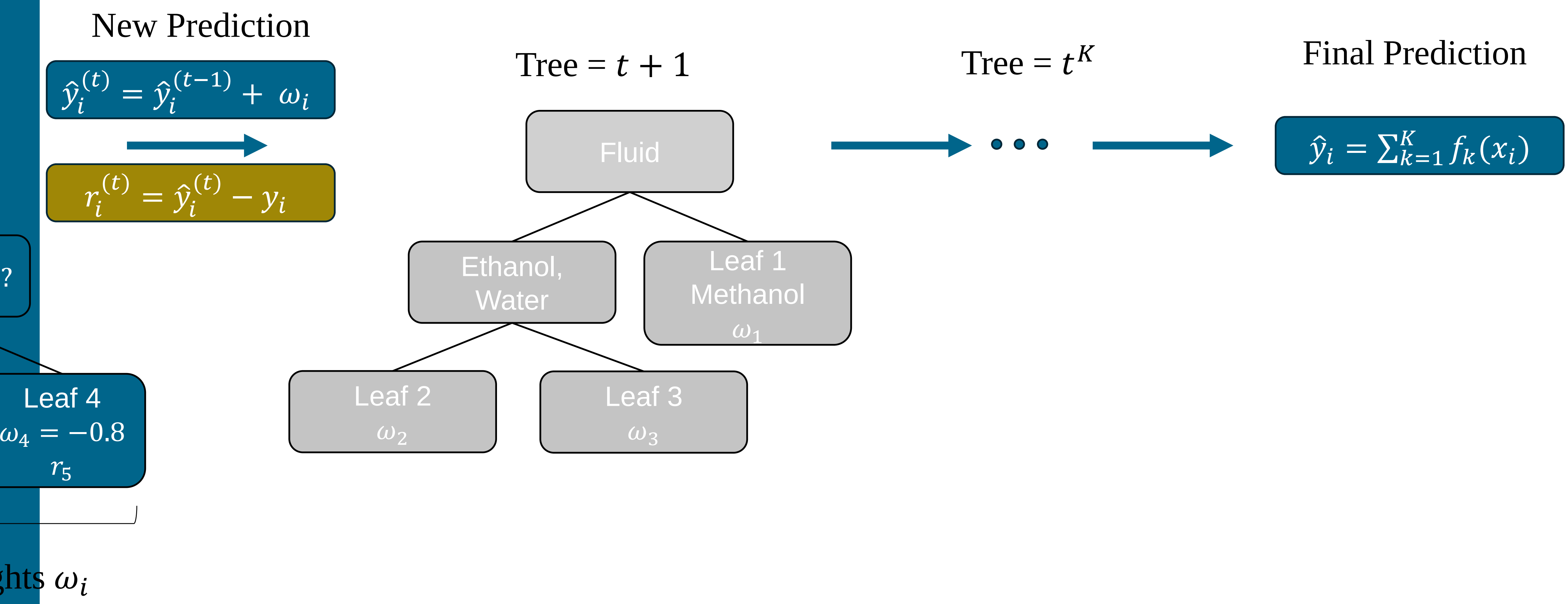
Case	New R_{th} Prediction
1	**1**
2	**0.85**
3	**0.548**
4	**0.548**
5	**0.2**

Thermal Resistance Prediction With Gradient Boosting



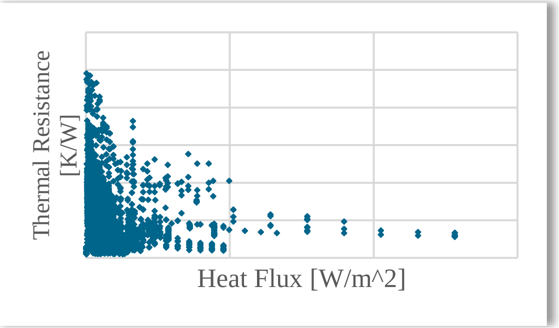
Clustering residuals and calculating weights ω_i

Thermal Resistance Prediction With Gradient Boosting



Thermal Resistance Prediction With Gradient Boosting

1
Data curation

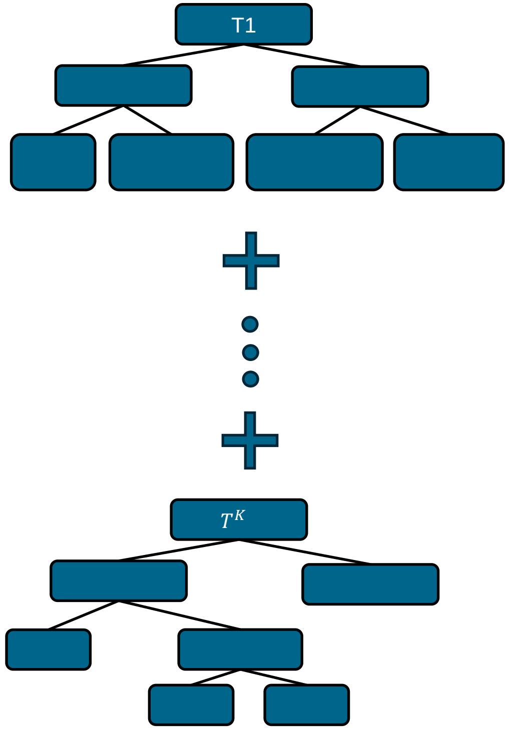


Data Split

Training 70%

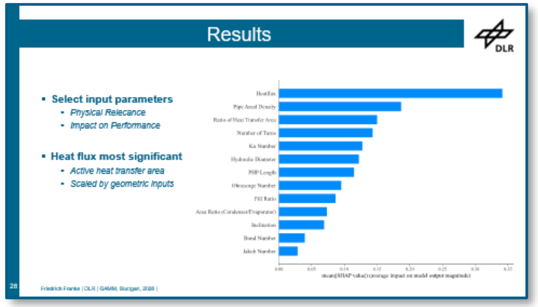
Test 30%

2
Model training



3
Testing & application

Result of Prediction

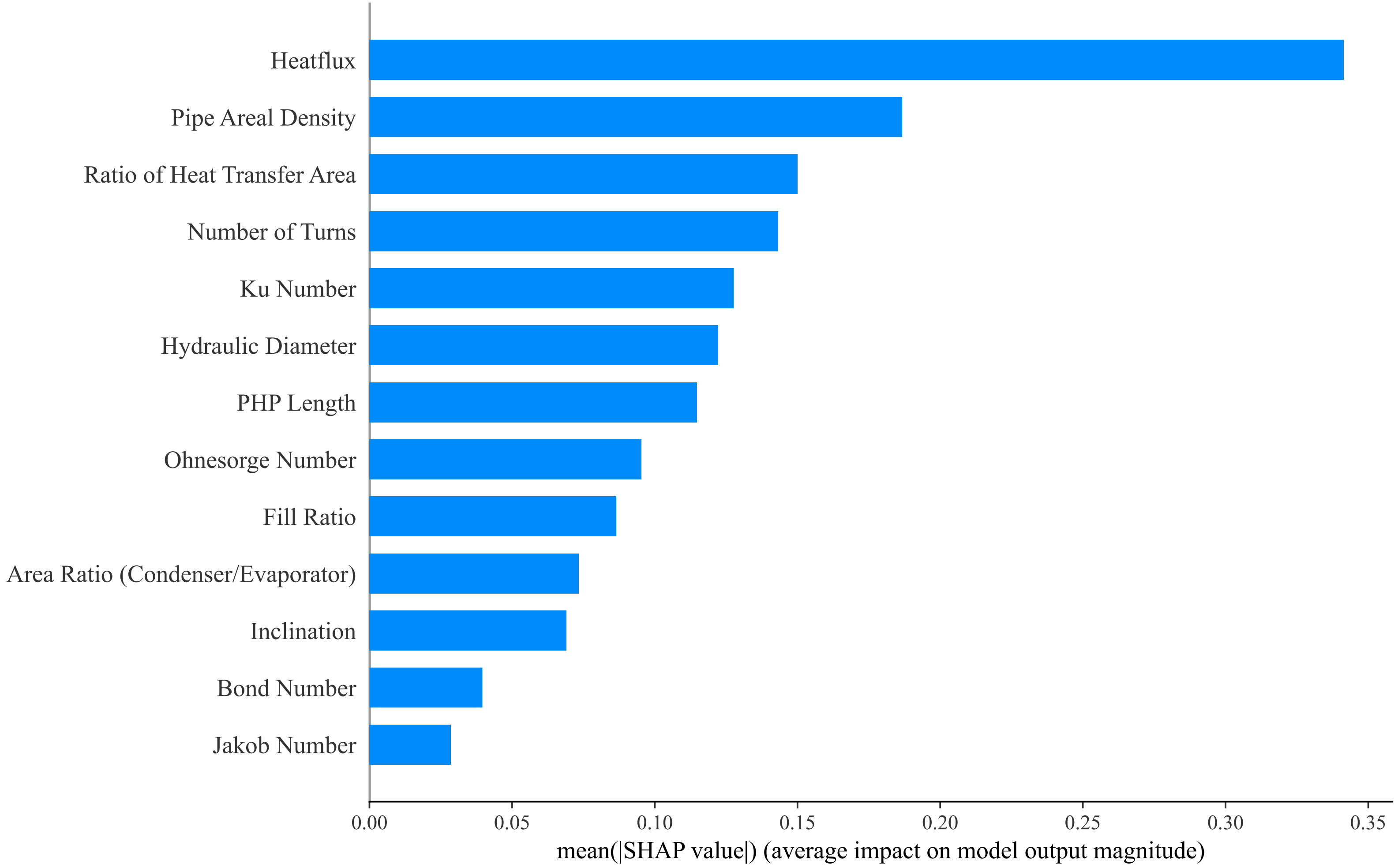


4
Validation & Expansion

Results

- **Select input parameters**
  - *Physical Relecance*
  - *Impact on Performance*

- **Heat flux most significant**
  - *Active heat transfer area*
  - *Scaled by geometric inputs*



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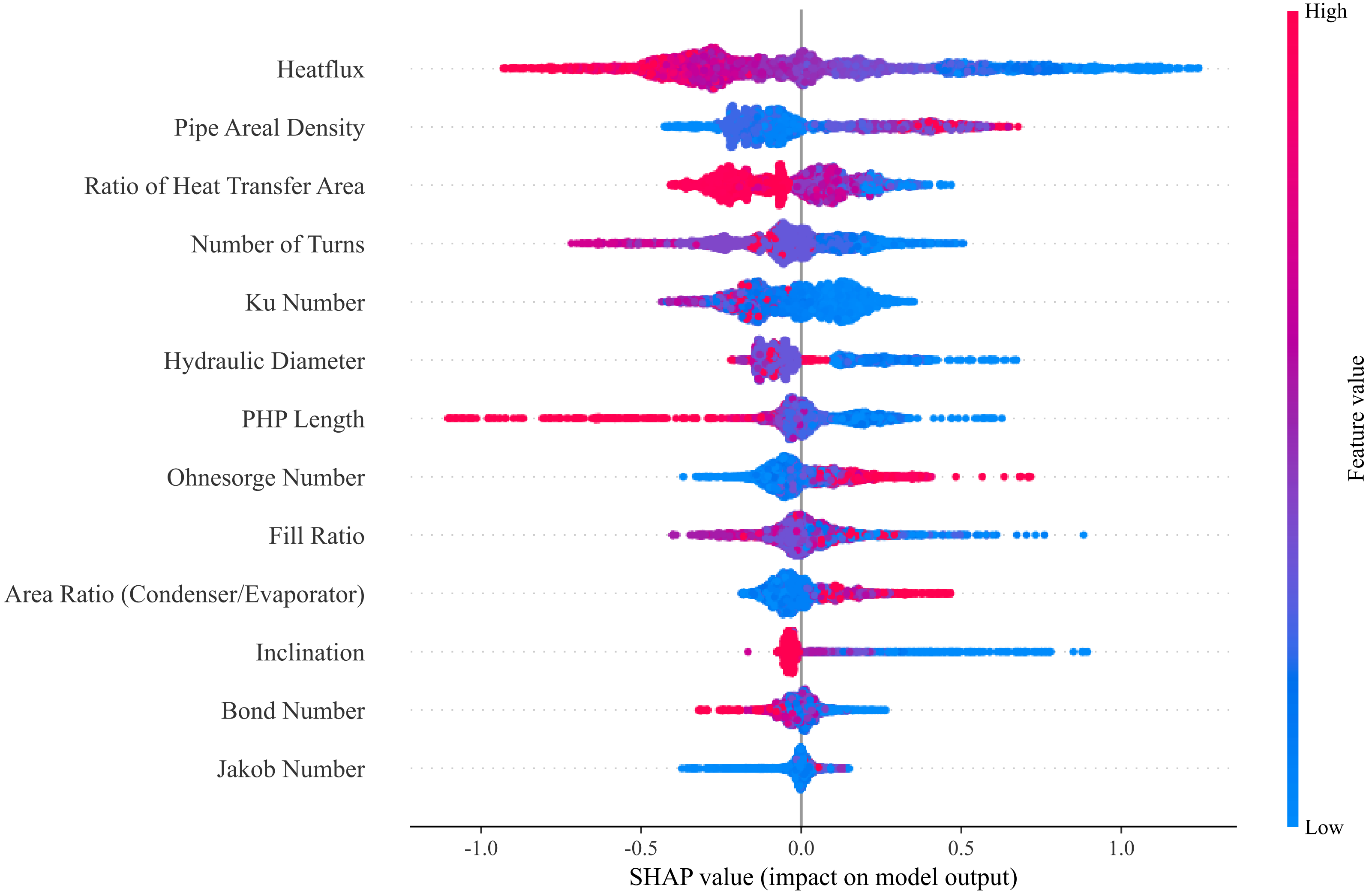
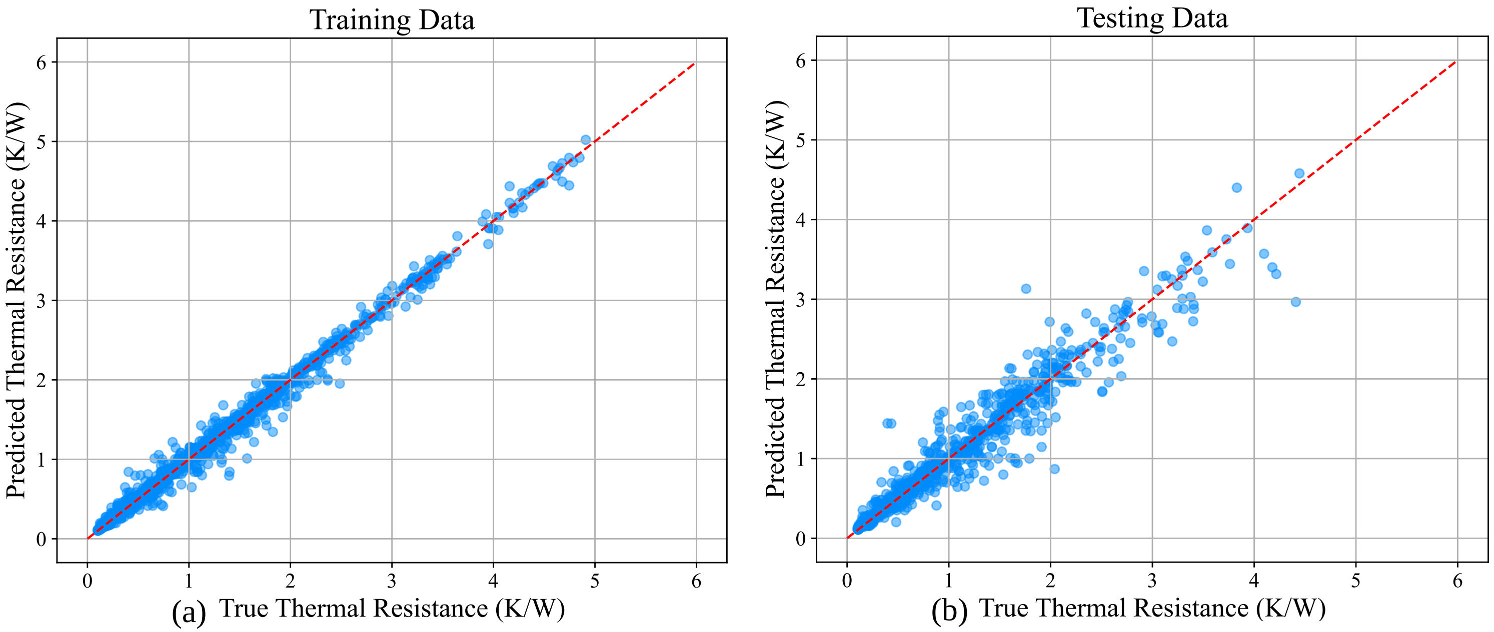


Results

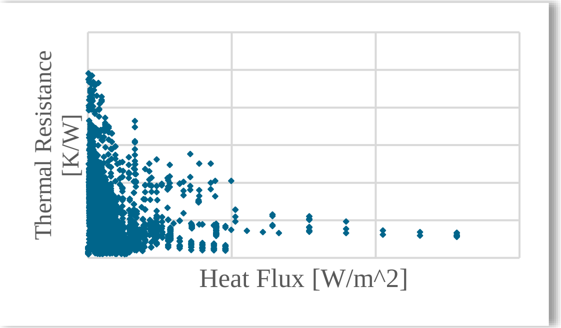
- **Select input parameters**
  - *Physical Relecance*
  - *Impact on Performance*
- **Heat flux most significant**
  - *Active heat transfer area*
  - *Scaled by geometric inputs*
- **Very high model accuracy**
  - *Mean Average Error =* $0.11\ K/W$
  - *Corresponds to approx 20% relative error*



Parity plots for model training (a) and testing (b)

Thermal Resistance Prediction With Gradient Boosting

1
Data selection



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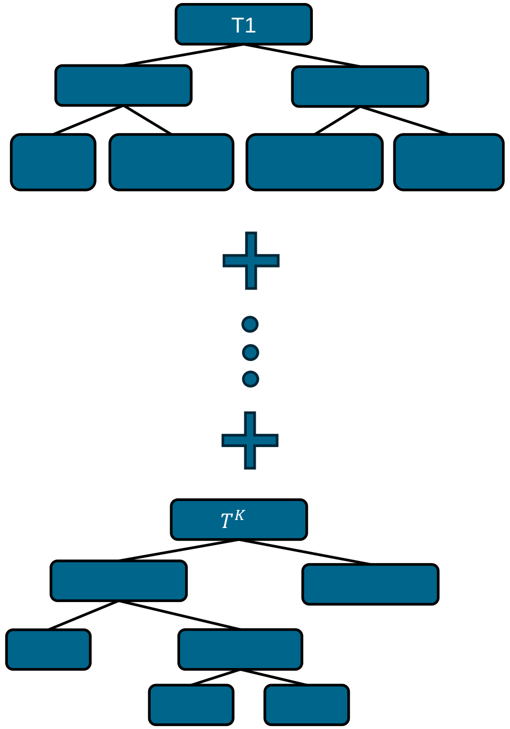

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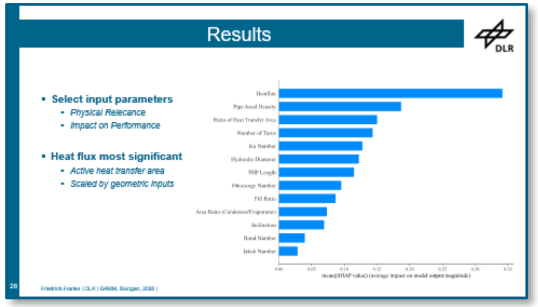
Testing & application

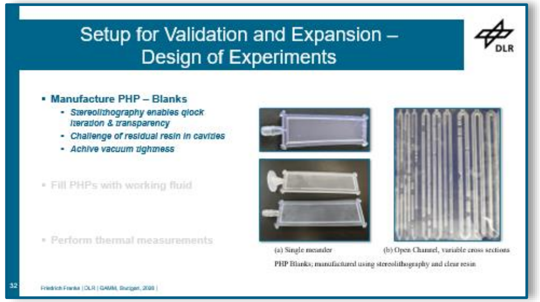
Result of Prediction



4
Validation & Expansion

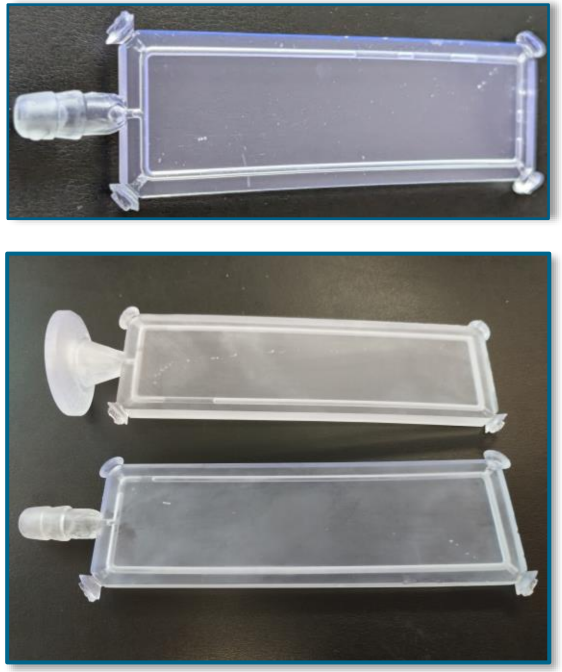
Validation

Expansion to new Geometries

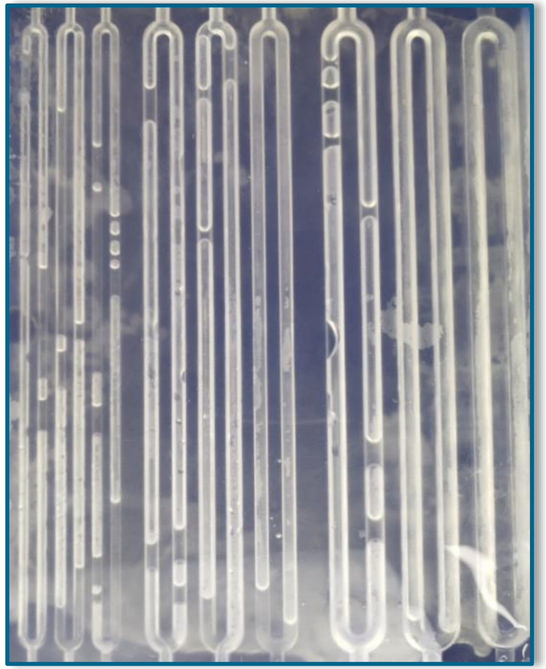


Setup for Validation and Expansion – Design of Experiments

- **Manufacture PHP – Blanks**
  - ***Stereolithography enables qiock iteration & transparency***
  - ***Challenge of residual resin in cavities***
  - ***Achive vacuum tightness***
- **Fill PHPs with working fluid**
- **Perform thermal measurements**



(a) Single meander

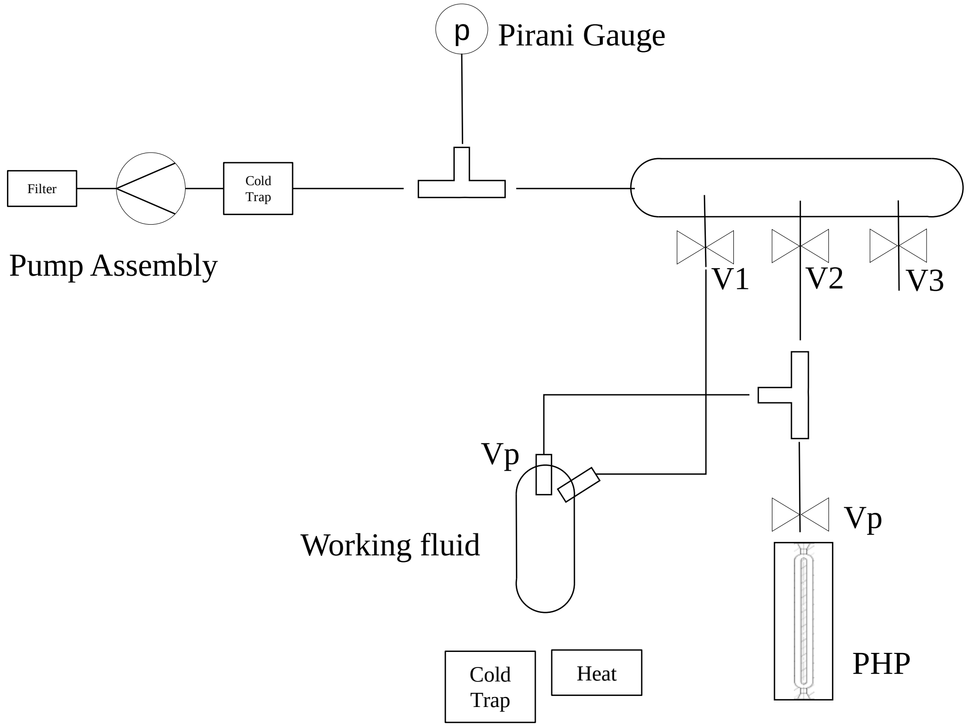


(b) Open Channel, variable cross sections

PHP Blanks; manufactured using stereolithography and clear resin

Setup for Validation and Expansion – Design of Experiments

- Manufacture PHP – Blanks
  - *Stereolithography enables qiock iteration & transparency*
  - *Challenge of residual resin in cavities*
  - *Achive vacuum tightness*
- **Fill PHPs with working fluid**
  - **Evacuate PHP to $p \leq 10^{-5} bar$**
  - **Degas working fluid & filling rig**
  - **Transfer working fluid**
  - **Seal PHP**
- Perform thermal measurements



Schematic of Filling rig

Setup for Validation and Expansion – Design of Experiments

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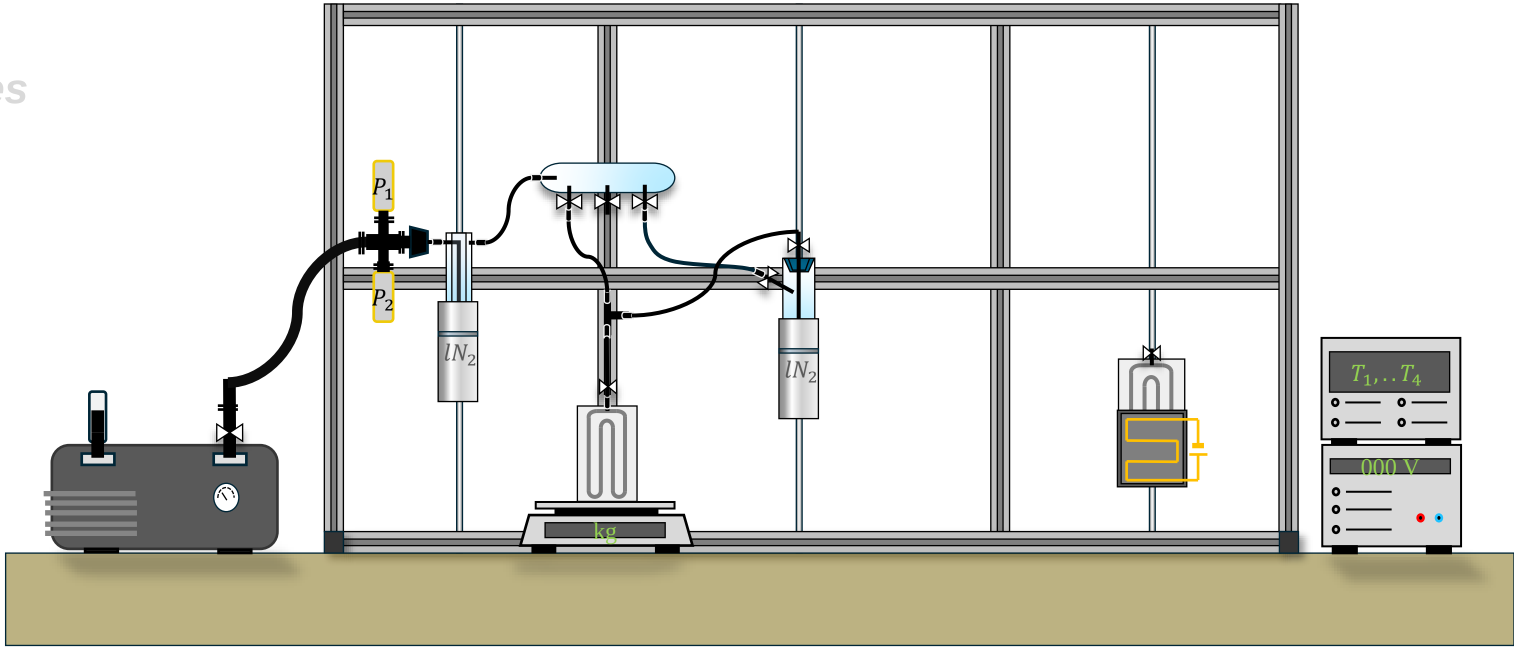

Schematic of filling rig

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Schematic of filling rig

Setup for Validation and Expansion – Design of Experiments

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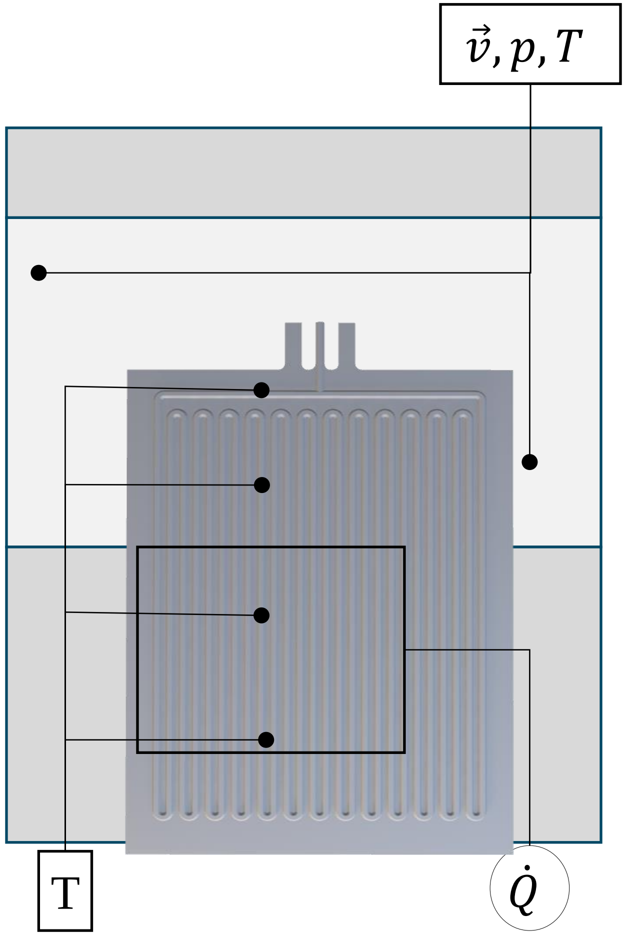
- Fill PHPs with working fluid
  - Evacuate PHP to $p \leq 10^{-5} bar$
  - Degas working fluid & filling rig
  - Transfer working fluid
  - Seal PHP
- **Perform thermal measurements**
  - Apply calibrated heat source and sink
  - Measure Temperature Distribution

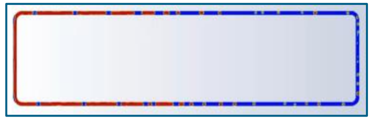


Schematic of thermal testing environment

Conclusions

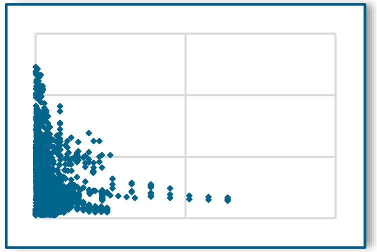
Gradient Boosting

Conventional simulation challenging



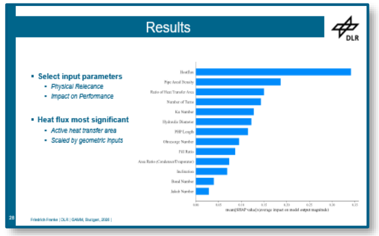
Large data set with 3441 cases

Collected from literature



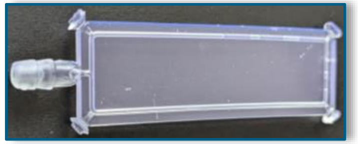
XG-Boost Model trained and tested

Tests show decent prediction capability rel. error $\approx 20\%$

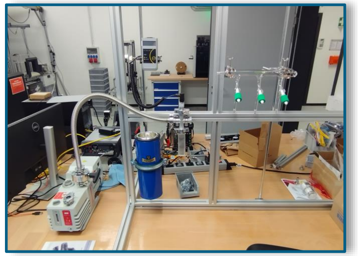


Experimental Iteration

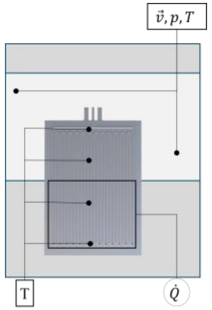
3D printing Manufacturing approach for experimental PHPs developed



Experimental setup for intermediate-vacuum filling built



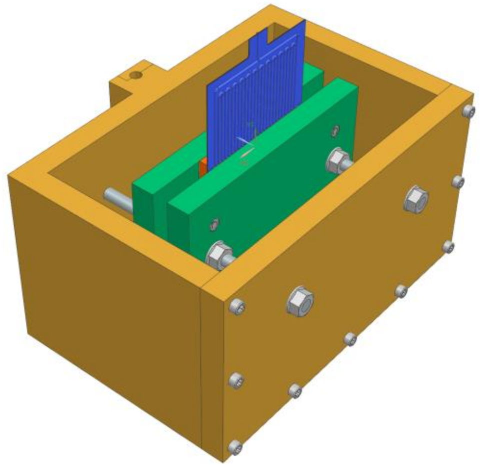
Test Bench for thermal measurements designed



Future Research

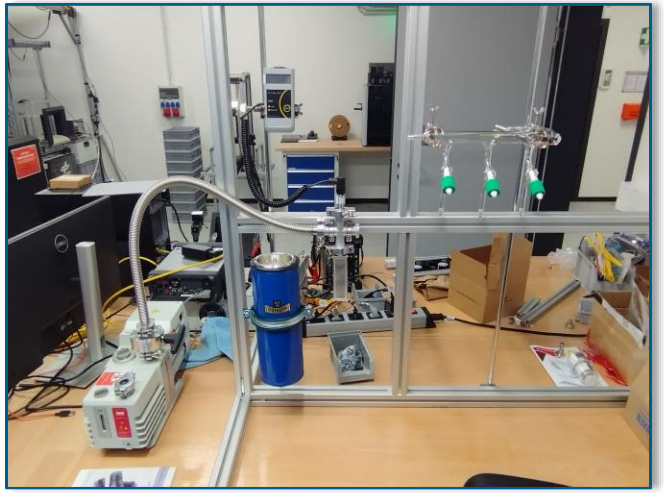
XG Boost Model

- Validate Predictions made by the Trained Model
- Expand the training data set using alternating cross sections



Trials

- Examine tightness and outgassing in transparent PHPs
- Perform Filling of Resin PHP
- Evaluate fluid behavior under heat load



Thank you for your attention!

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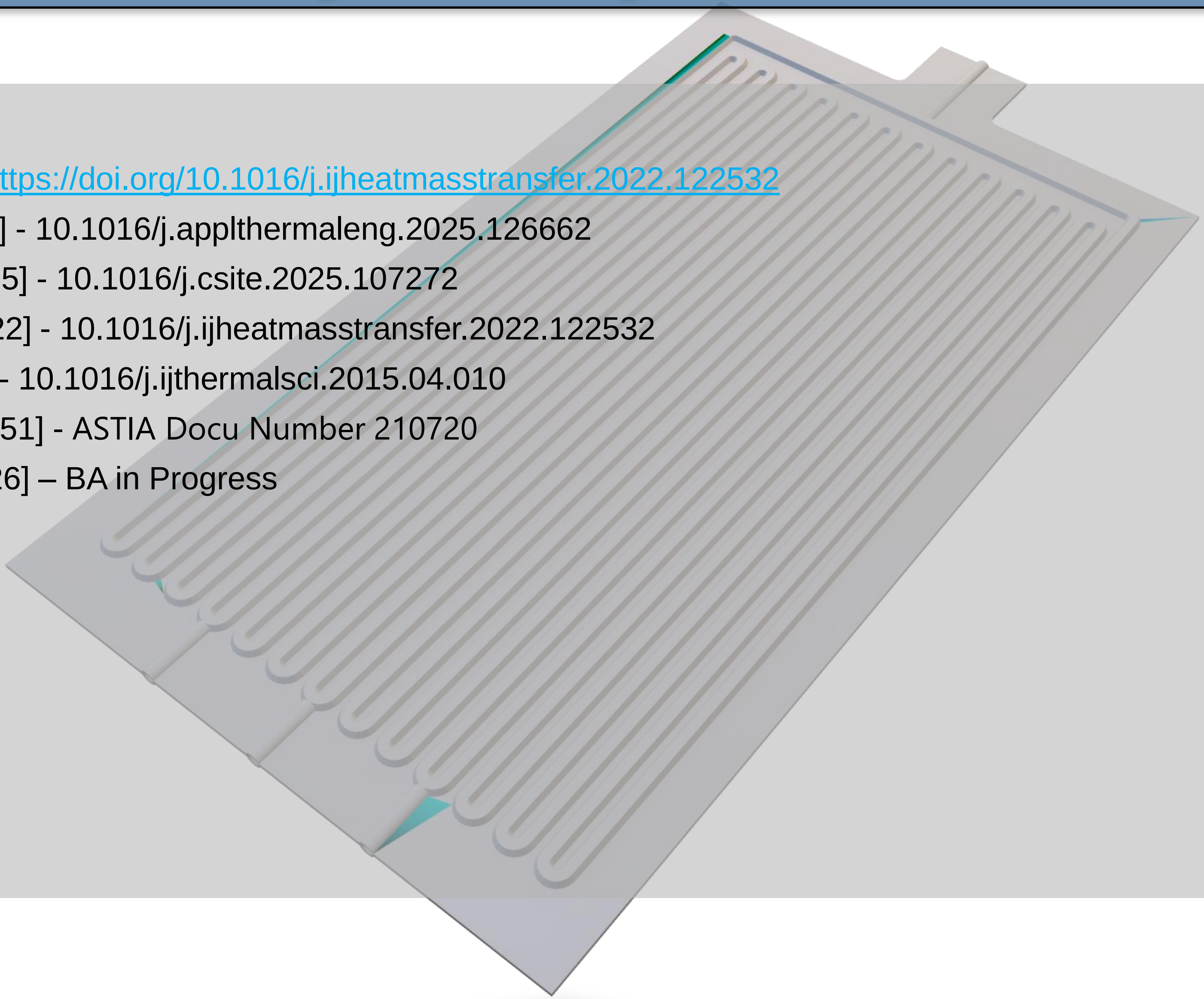
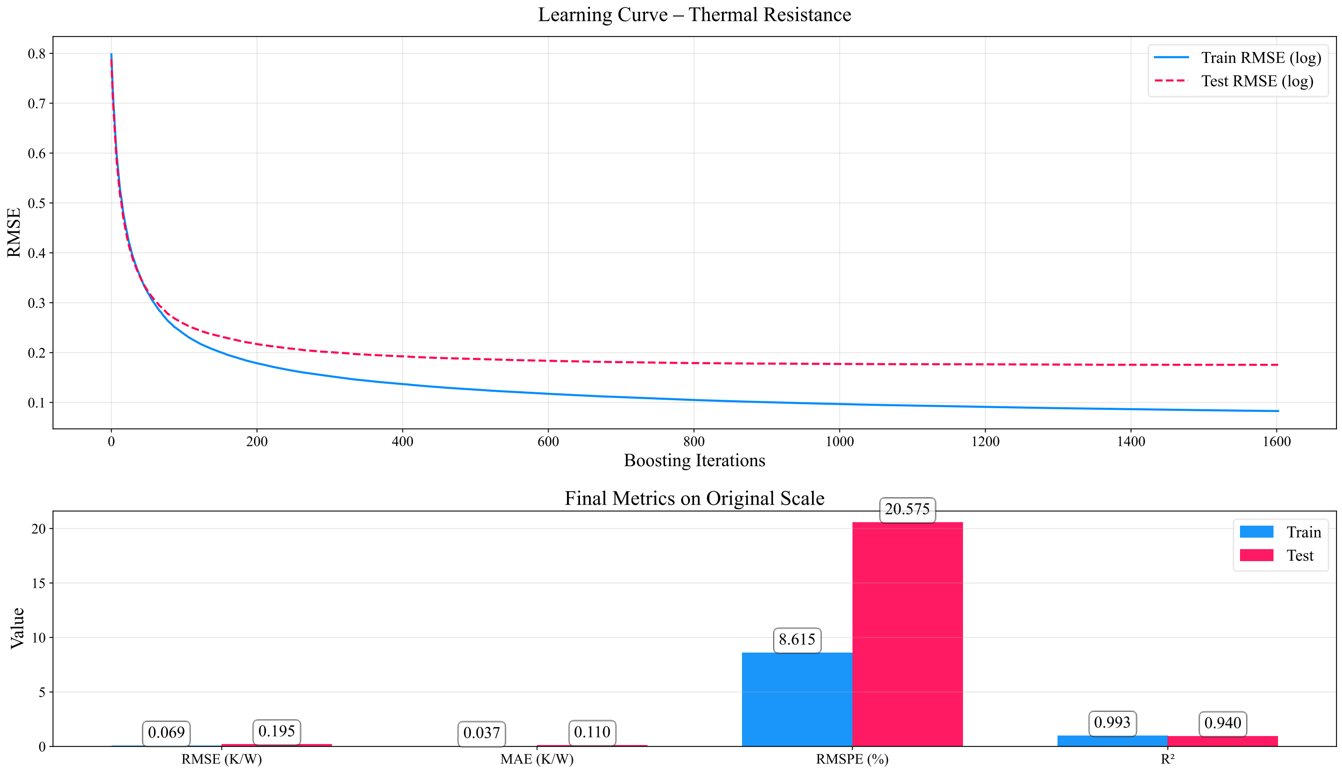
- **Sources**

  - [Li 2023] - https://doi.org/10.1016/j.ijheatmasstransfer.2022.122532
  - [Aziza 2025] - 10.1016/j.applthermaleng.2025.126662
  - [Franke 2025] - 10.1016/j.csite.2025.107272
  - [Mameli 2022] - 10.1016/j.ijheatmasstransfer.2022.122532
  - [Ayel 2021] - 10.1016/j.ijthermalsci.2015.04.010
  - [Shapley 1951] - ASTIA Docu Number 210720
  - [Illbruck 2026] – BA in Progress



Results

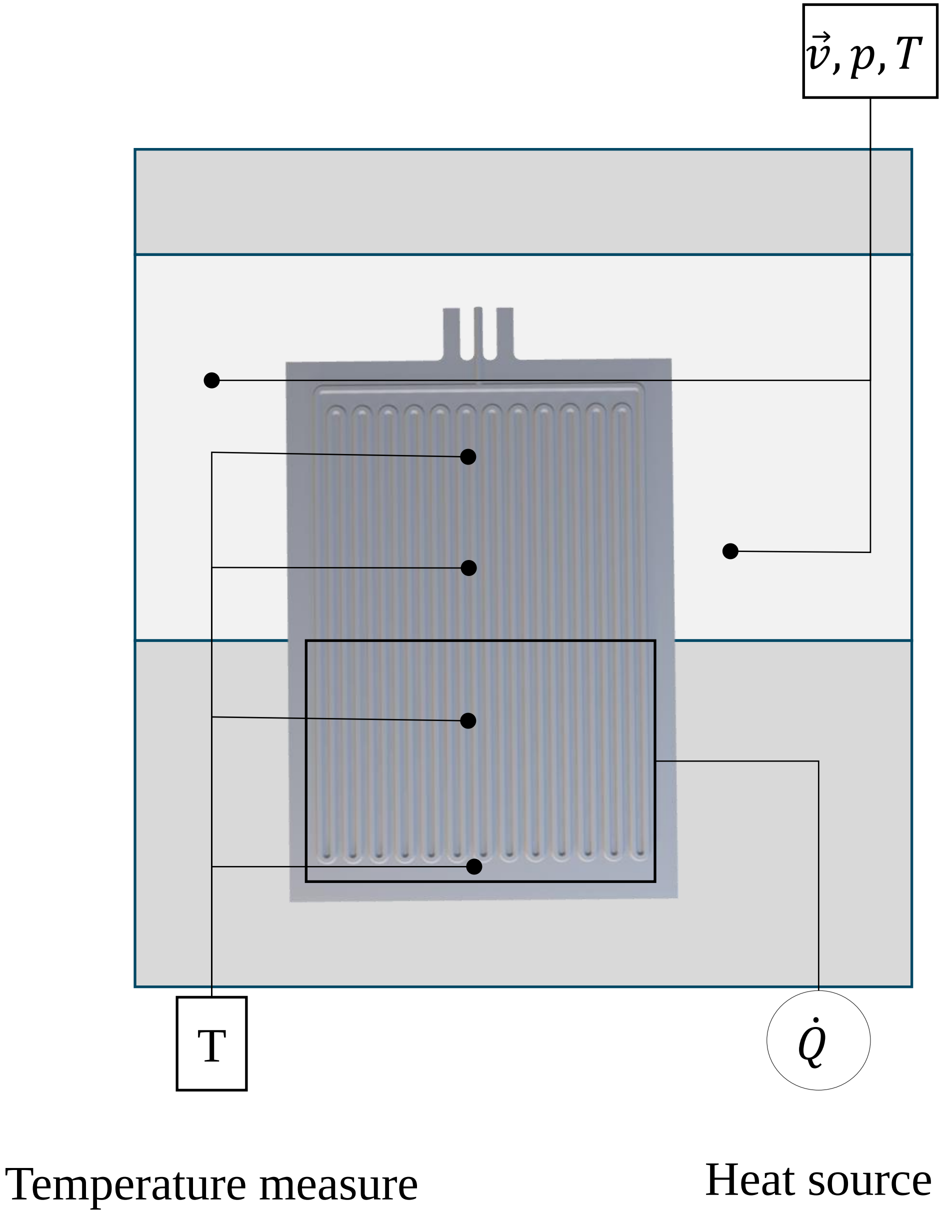
- **Select input parameters**
  - *Physical relevance*
  - *Impact on performance*
- **Heat flux most significant**
  - *Active heat transfer area*
  - *Scaled by geometric inputs*
- **Very high model accuracy**
  - *Mean Average Error* $= \ 0.11\ K/W$
  - *Corresponds to approx 20% relative error*



Measuring Performance

(1) IPM & (2) – TMT MAD

1. Temperature Sensors on outer wall
2. IR-camera (frontal view)
3. Testing Procedure: Stepwise increase of heating power at constant airspeed
4. Alter fan power
5. Install channel obstruction / Dummy stack



Simultaneous tests

Second test

1. Single Meander Tests
2. High speed, High Zoom Camera
3. Evt. High viscous, low evaporation temperature
4. Investigate varying channel cross section
5. Bubble behaviour
6. Oscillation and wall wetting phenomena