

Heat Pipe Assisted Air Cooling for Fuel Cells in Aviation

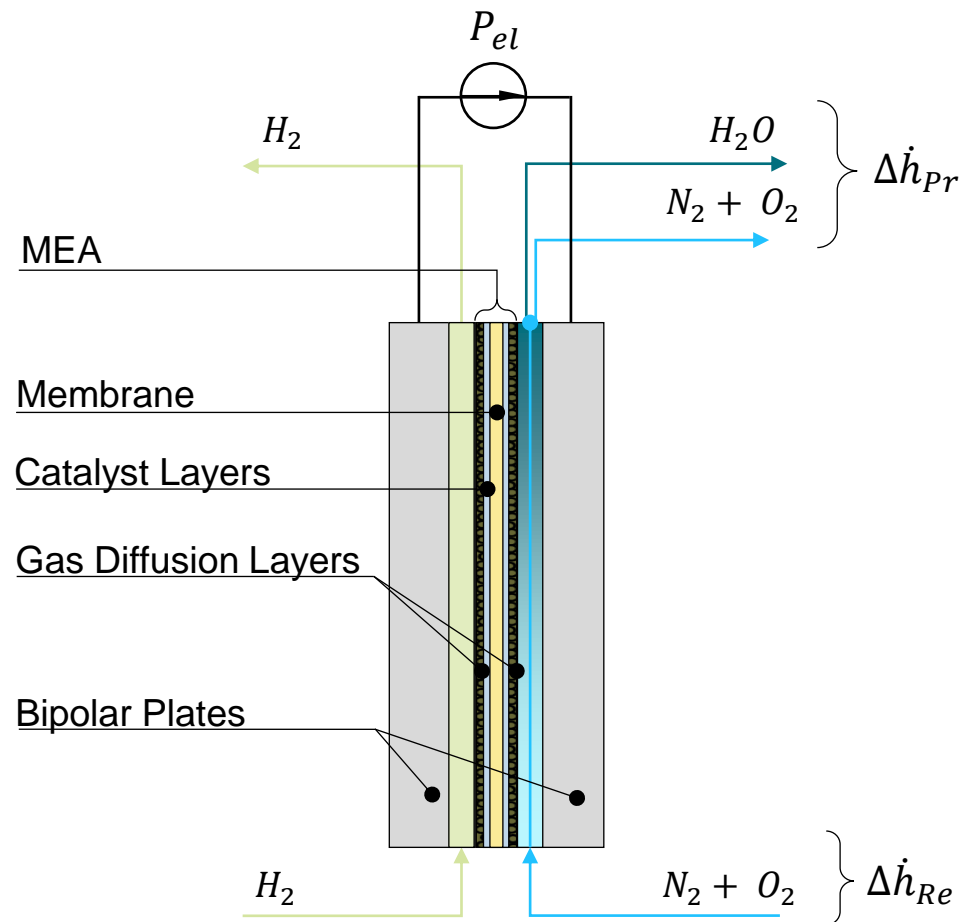
Friedrich Franke | DLR | Madrid 2025

Heat Pipe Assisted Air Cooling for Fuel Cells in Aviation

- **Introduction**
- **Motivation & State of the Art**
- **Methodology**
- **Results**
- **Conclusion & Outlook**

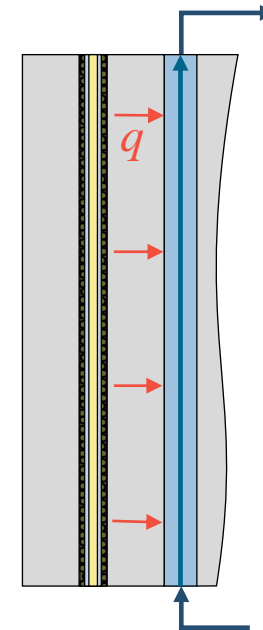


Introduction: Thermal Management for Fuel Cells

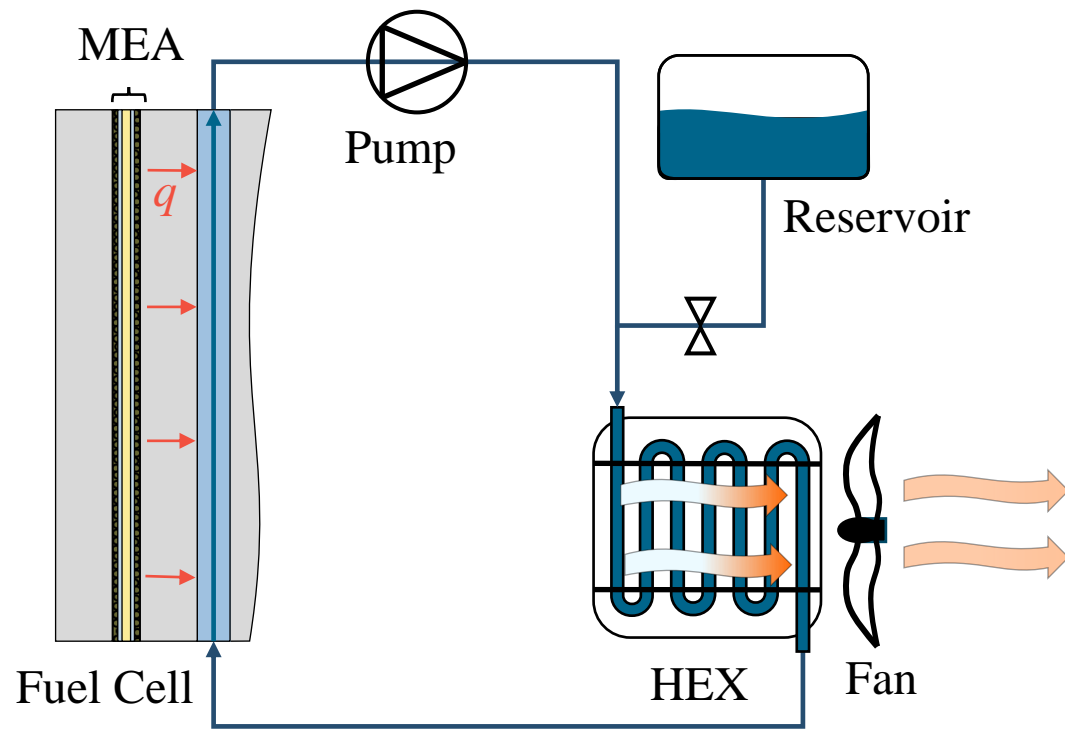


Introduction: Thermal Management for Fuel Cells

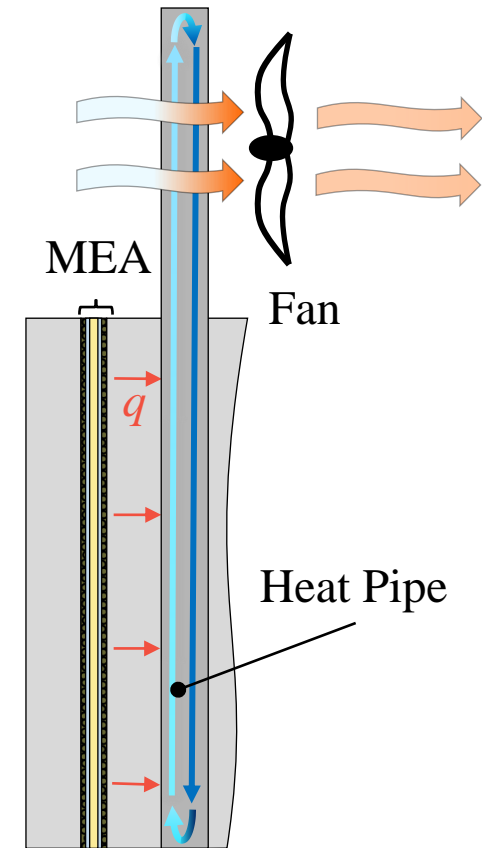
- **≈ 50% of the Hydrogen's energy is converted into heat in the catalyst layer**
- **Heat needs to be absorbed and rejected to the environment**
- **State of the art: Liquid cooling channels are installed in the bipolar plates**



Thermal Management for Fuel Cells

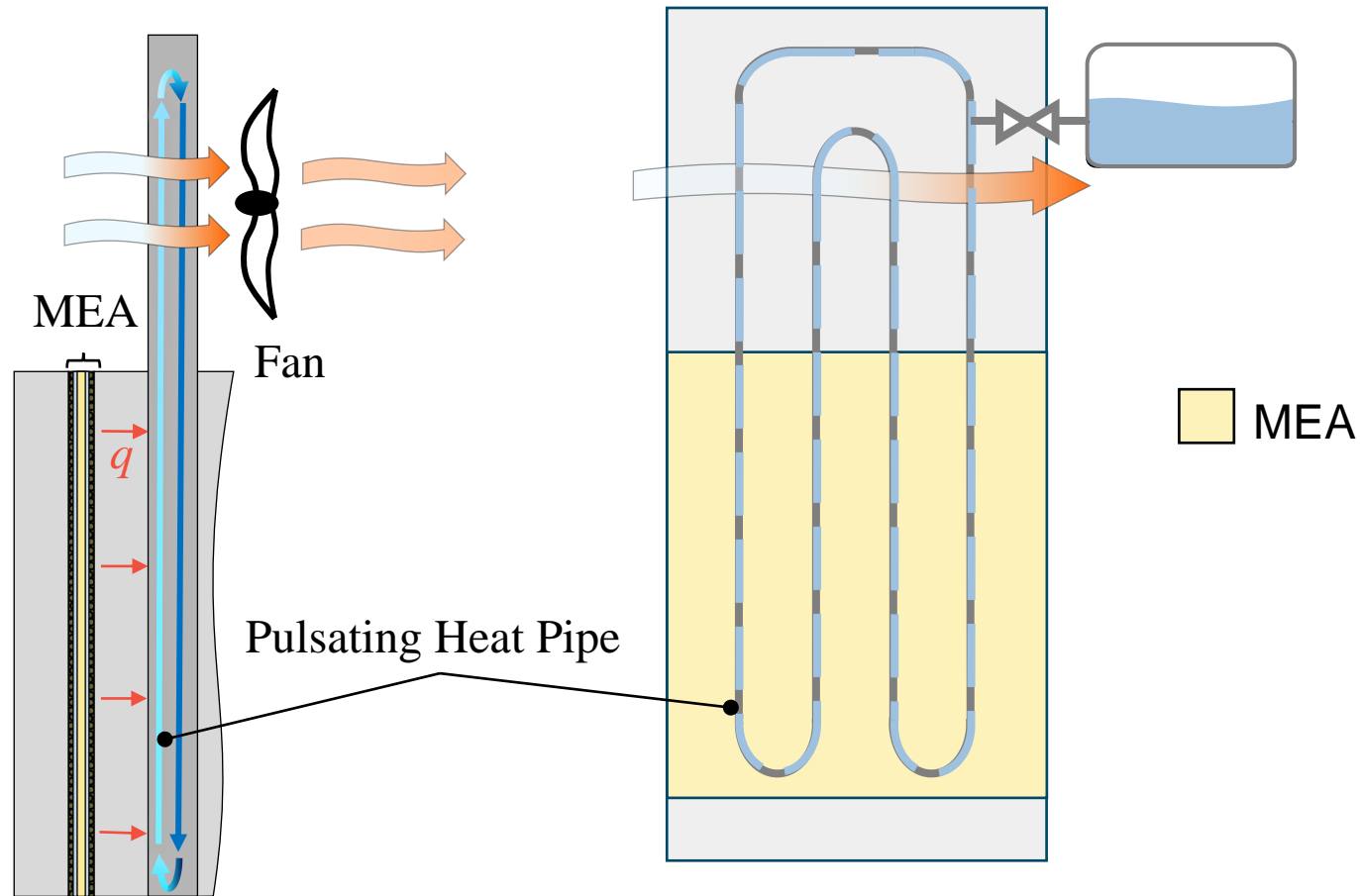


(a) Liquid cooling system

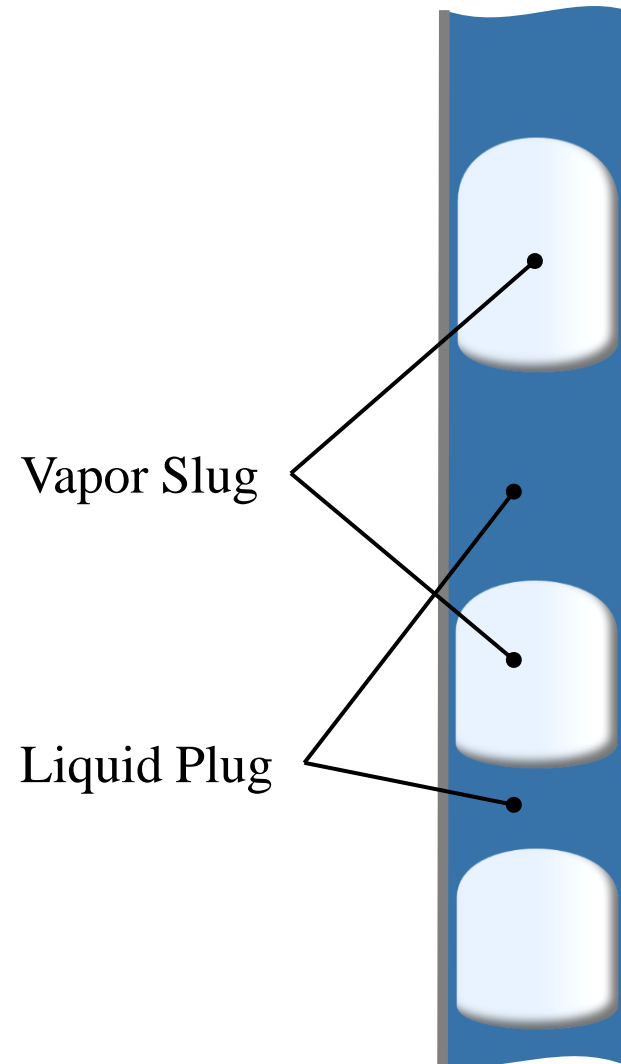


(b) Heat pipe assisted air cooling
[Supra 2014, Burke 2010]

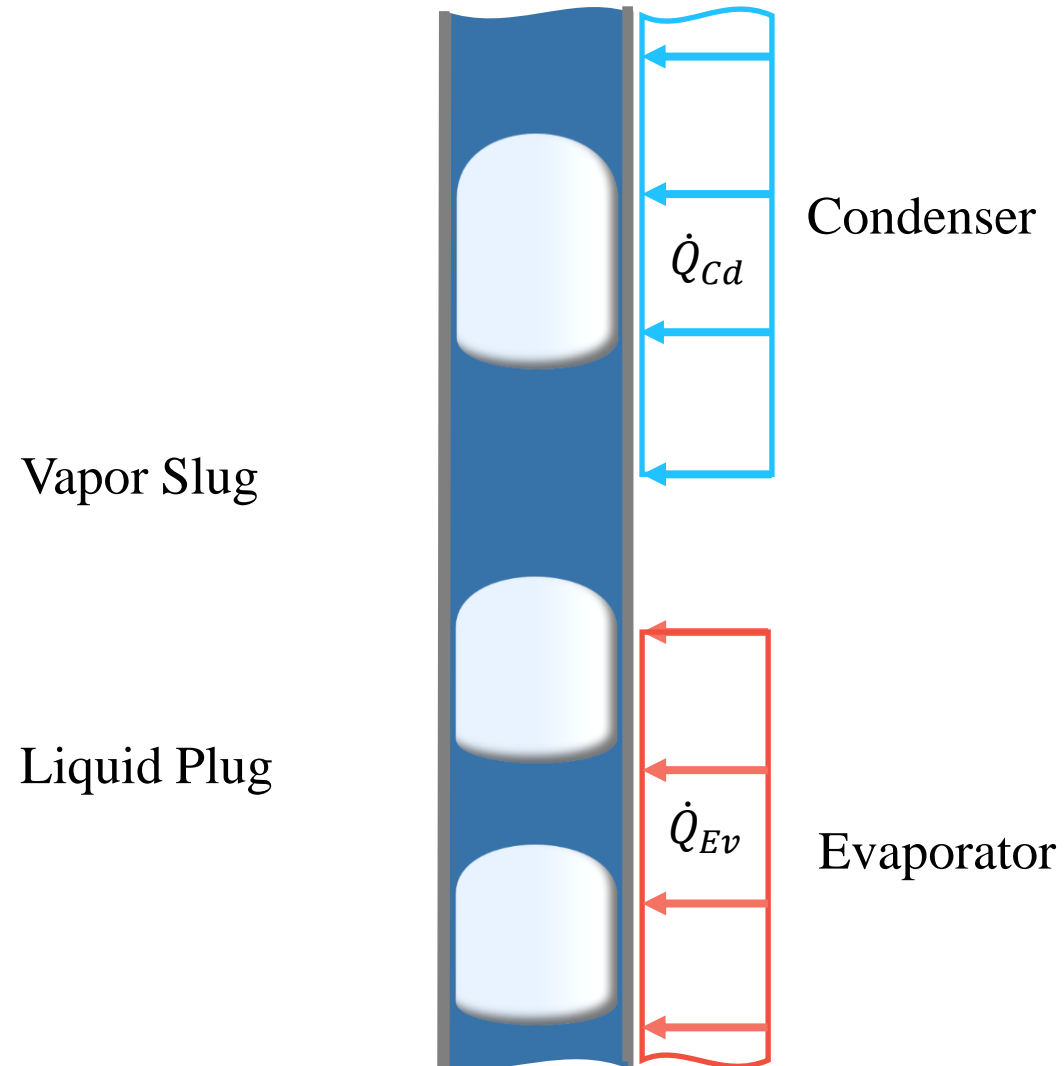
Pulsating Heat Pipe (PHP) Integration



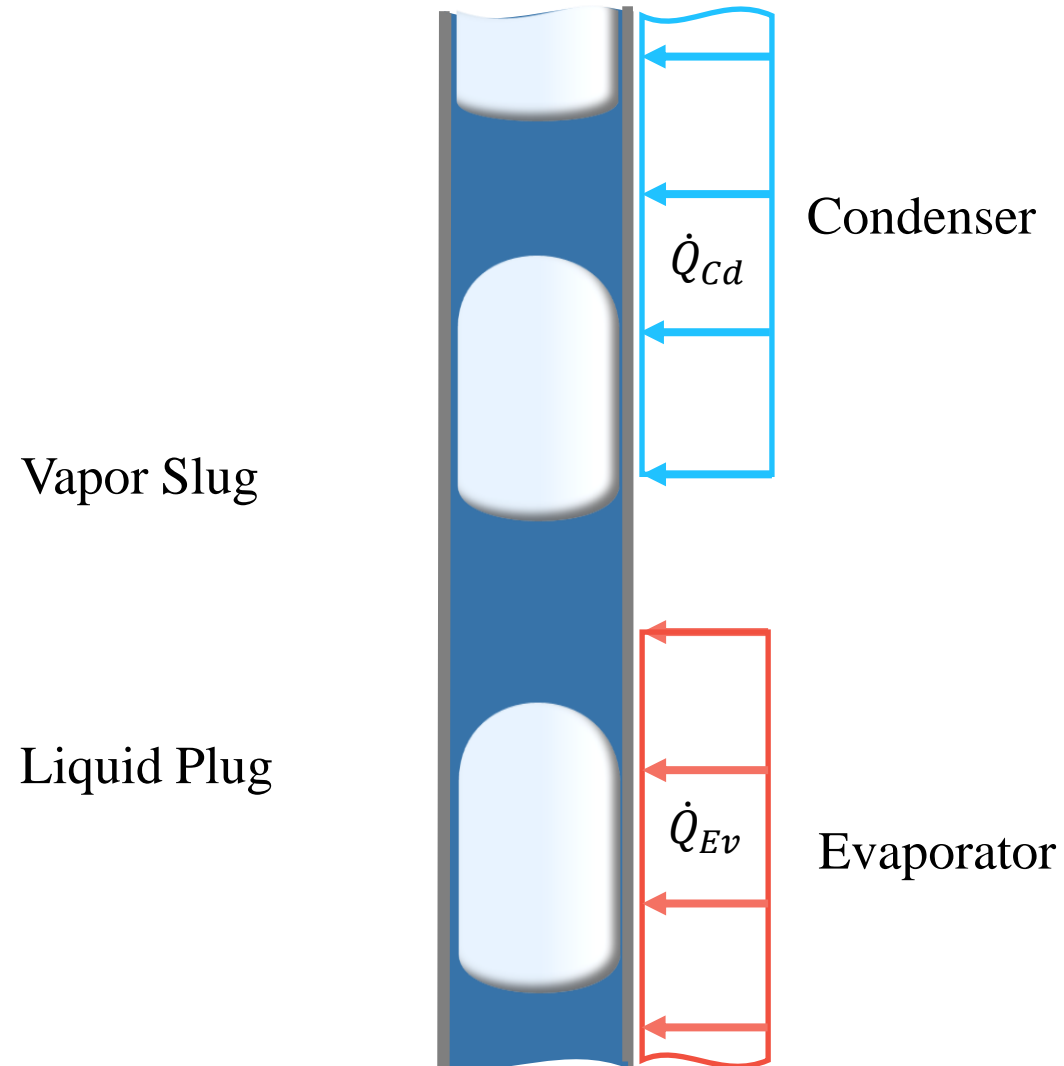
PHP Working Principle



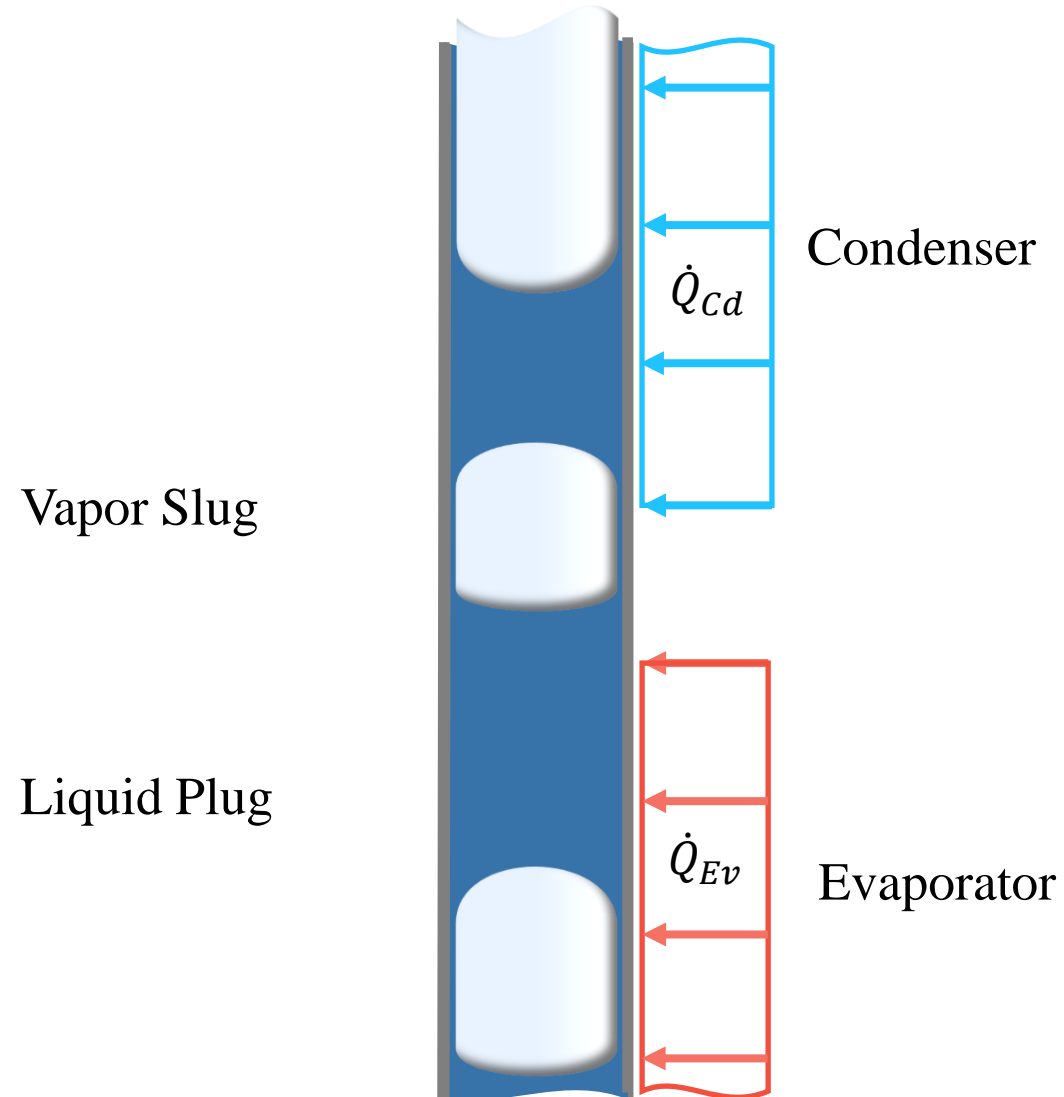
PHP Working Principle



PHP Working Principle

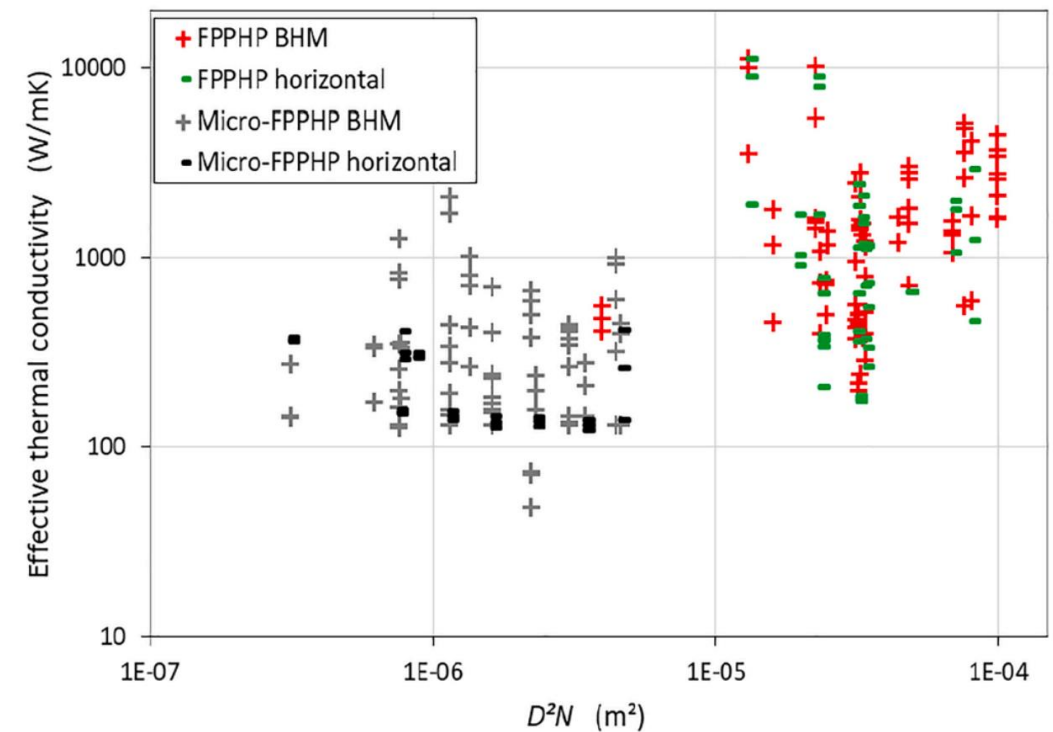


PHP Working Principle



State of Research in PHPs

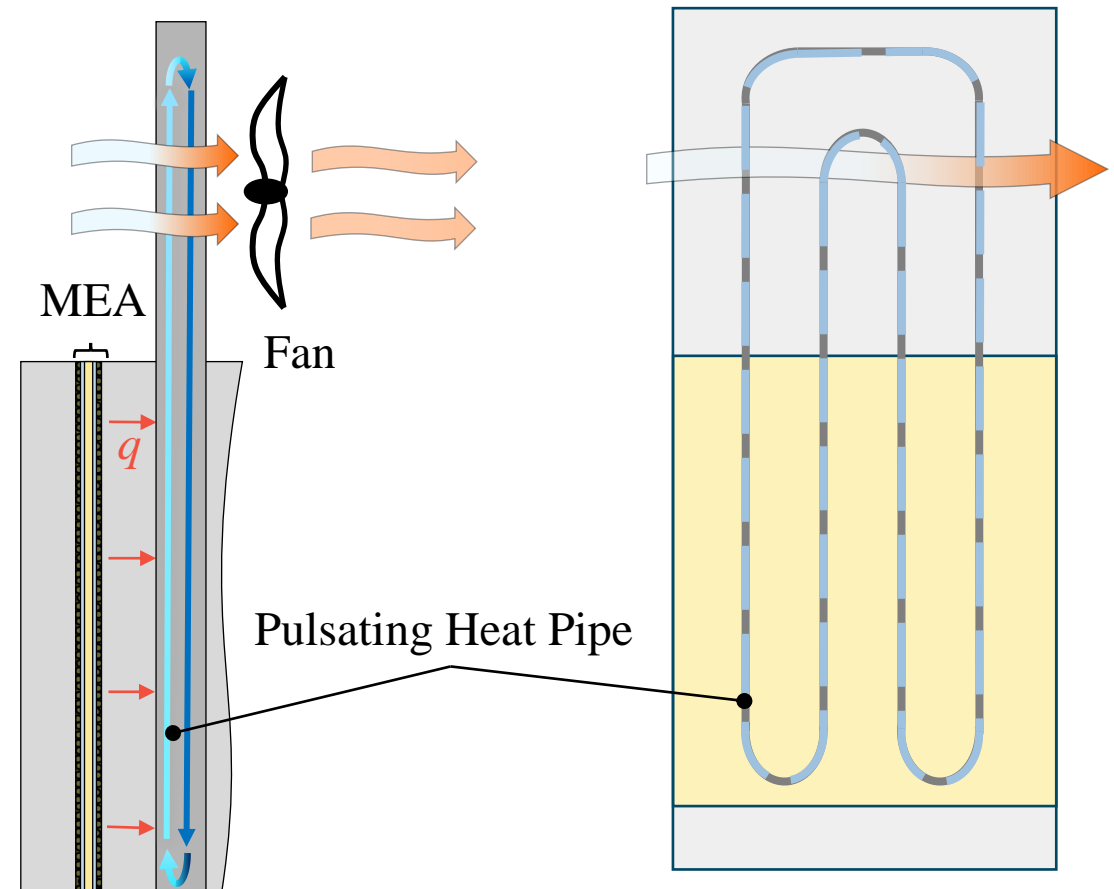
- Research into circular and rectangular PHPs
- Application in cooling of electronics
- Large variation in thermal performances [Ayel 2021]
- Simulation of internal behavior remains challenging [Nikolayev 2021]



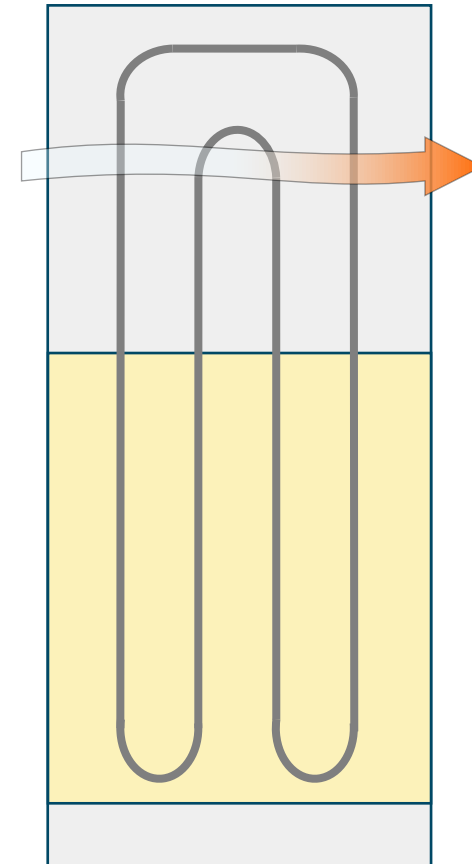
Equivalent thermal conductivities; data from [Ayel 2021]

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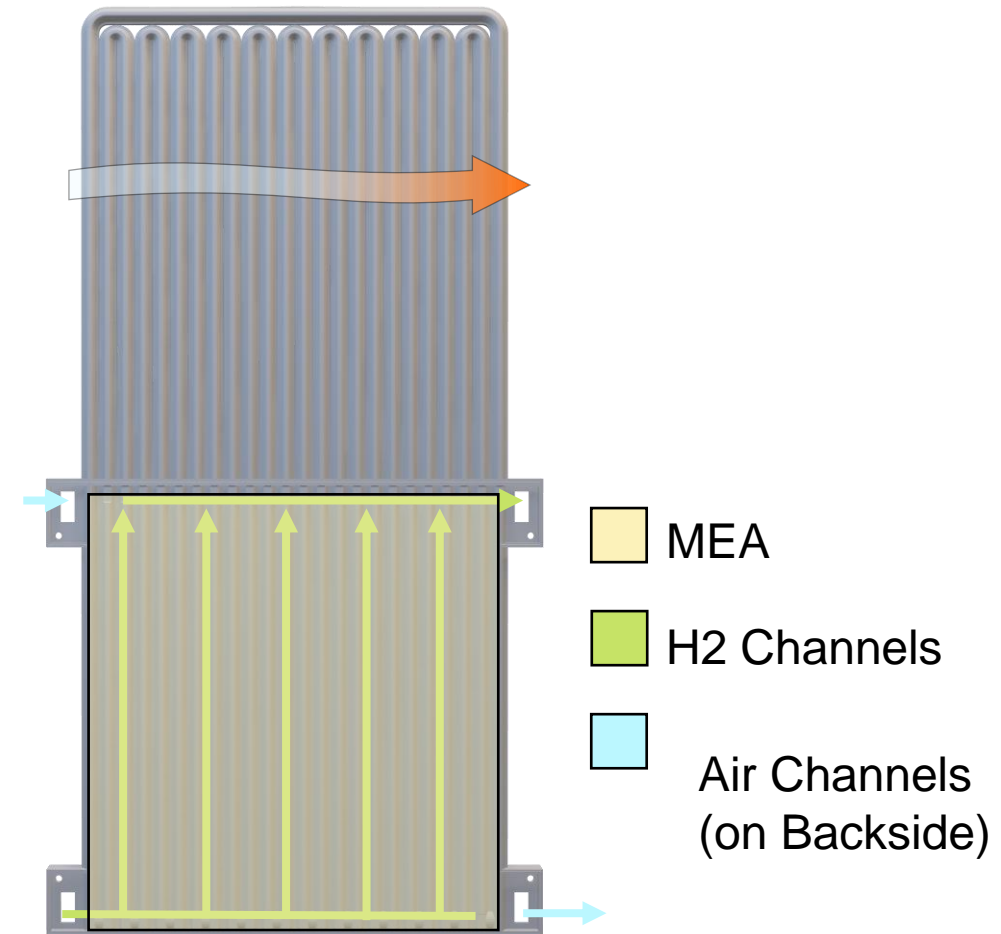


- **Design Geometry for PHP-Integrated Bipolar Plates**



Development of a Thermal Model

- **Design Geometry for PHP-Integrated Bipolar Plates**



Development of a Thermal Model

- **Design Geometry for PHP-Integrated Bipolar Plates**

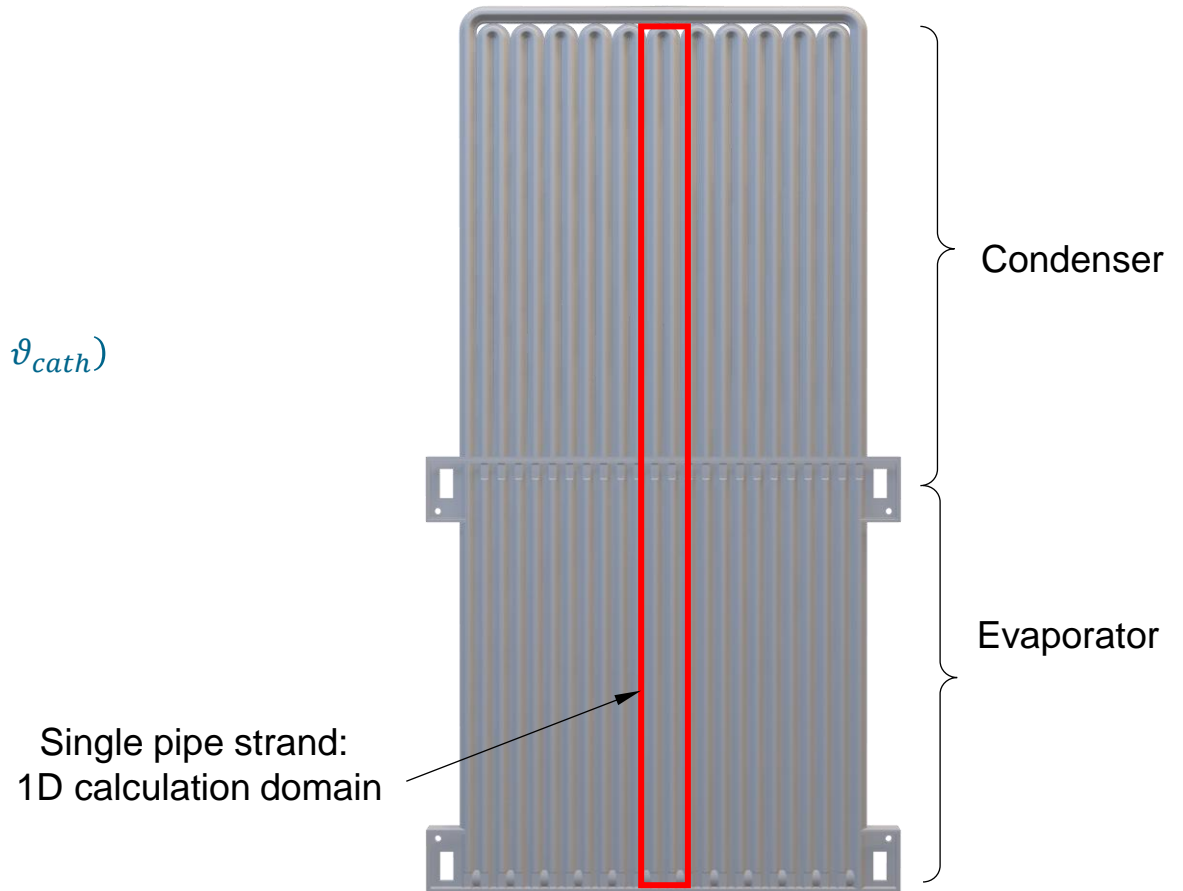
- **1D-Simplificatoin**

Evaporator

$$cQ \frac{\partial \vartheta}{\partial t} = \lambda_{eq} \nabla^2 \vartheta + \dot{W}_{MEA} + \dot{W}_{H_2}(\vartheta - \vartheta_{H_2}) + \dot{W}_{cath}(\vartheta - \vartheta_{cath})$$

Condenser

$$cQ \frac{\partial \vartheta}{\partial t} = \lambda_{eq} \nabla^2 \vartheta + \dot{W}_{Air}(\vartheta)$$



- **Design Geometry for PHP-Integrated Bipolar Plates**

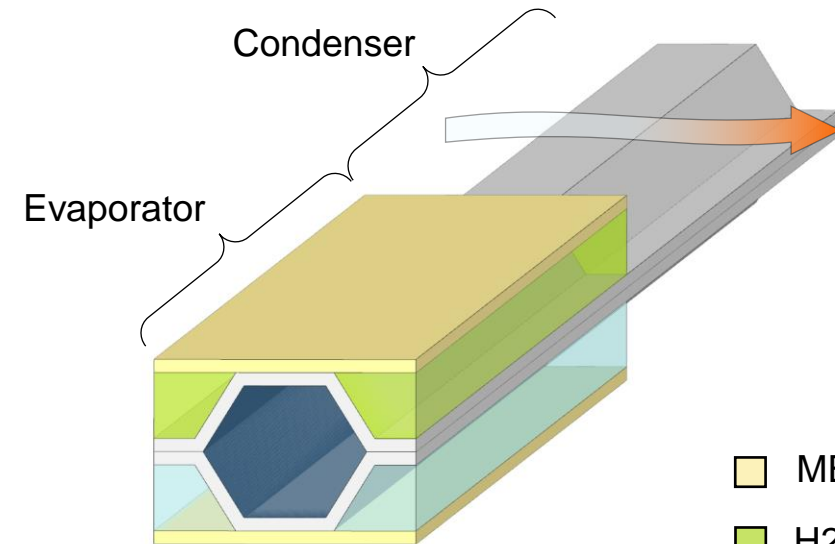
- **1D-Simplification**

Evaporator

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Condenser

$$cQ \frac{\partial \vartheta}{\partial t} = \lambda_{eq} \nabla^2 \vartheta + \dot{W}_{Air}(\vartheta)$$



Single pipe strand: 1D calculation domain

- MEA
- H2 Channels
- Air Channels (on Backside)

Development of a Thermal Model

- **Design Geometry for PHP-Integrated Bipolar Plates**

- **1D-Simplification**

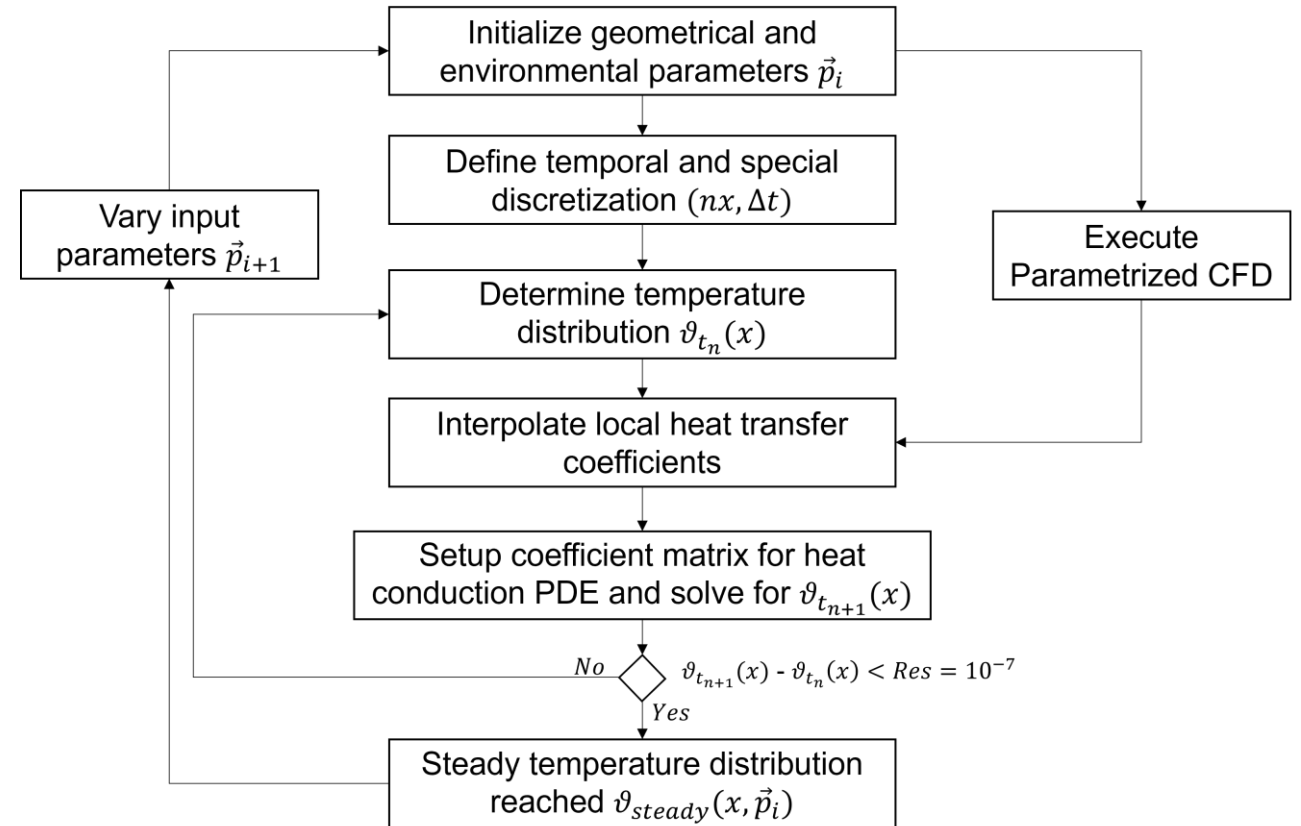
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- **Calculation of Convective Heat Transfer via CFD**



Development of a Thermal Model

- **Design Geometry for PHP-Integrated Bipolar Plates**

- **1D-Simplificatoin**

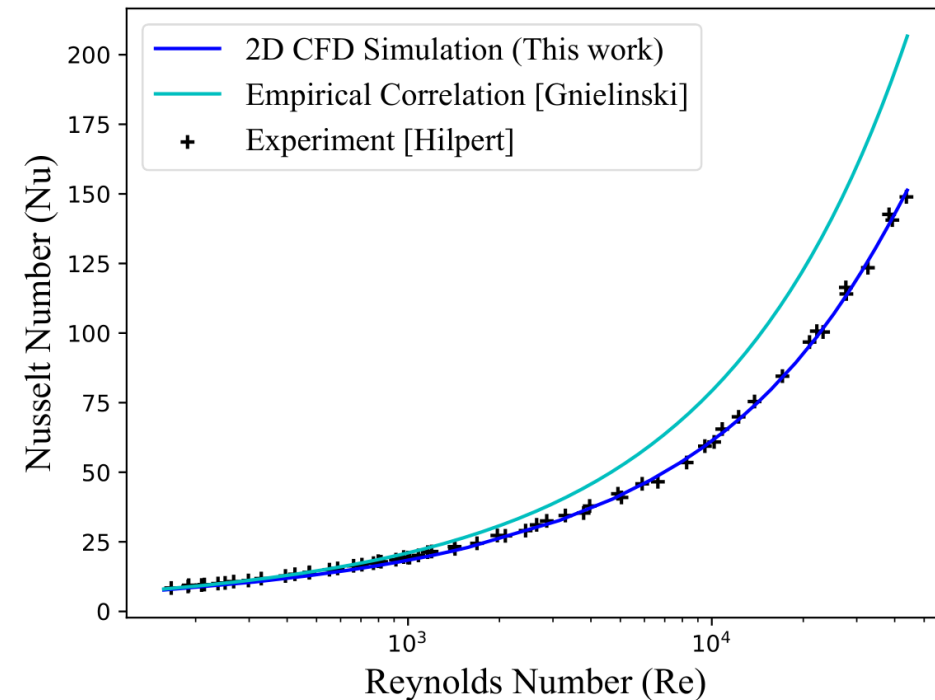
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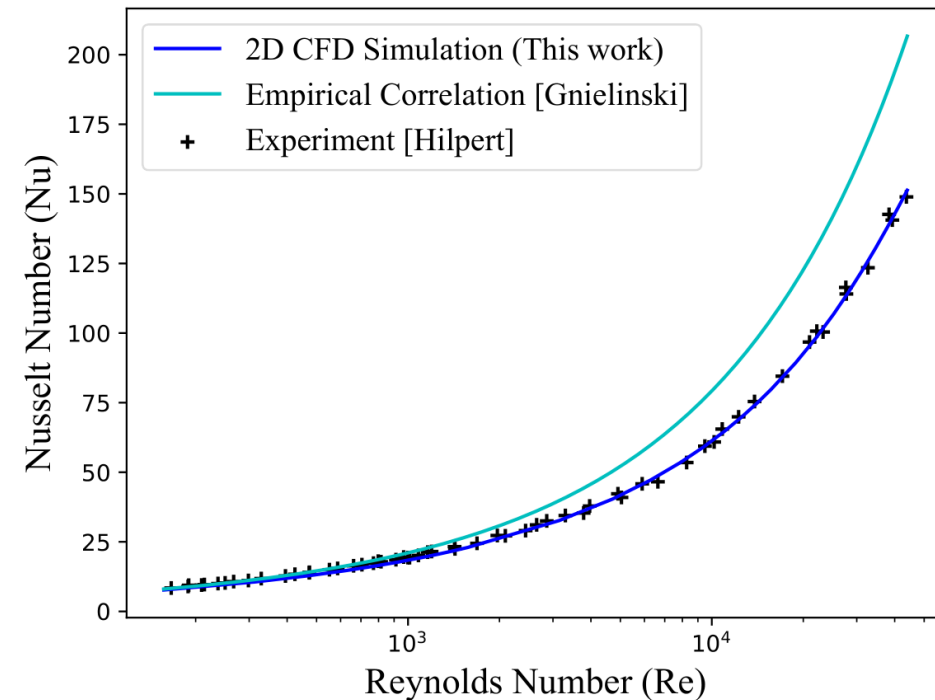
- **Calculation of Convective Heat Transfer via CFD**



Validation of Heat Transfer Coefficient Calculation; Based on Experimental Data from [Hilpert 1933]

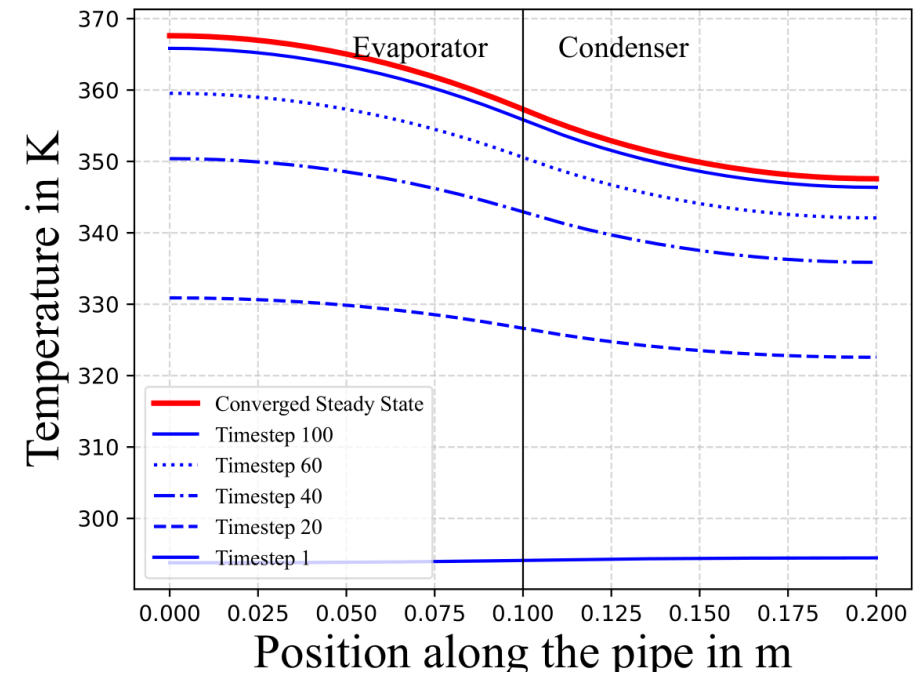
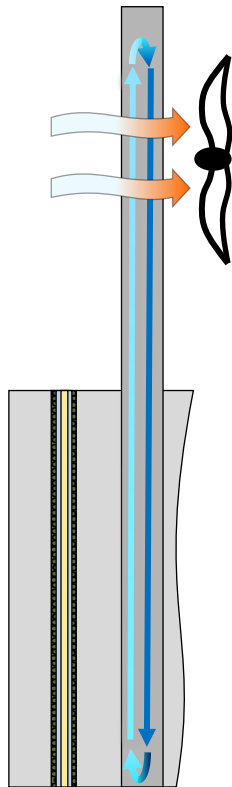
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Results

Temperature distribution along the PHP

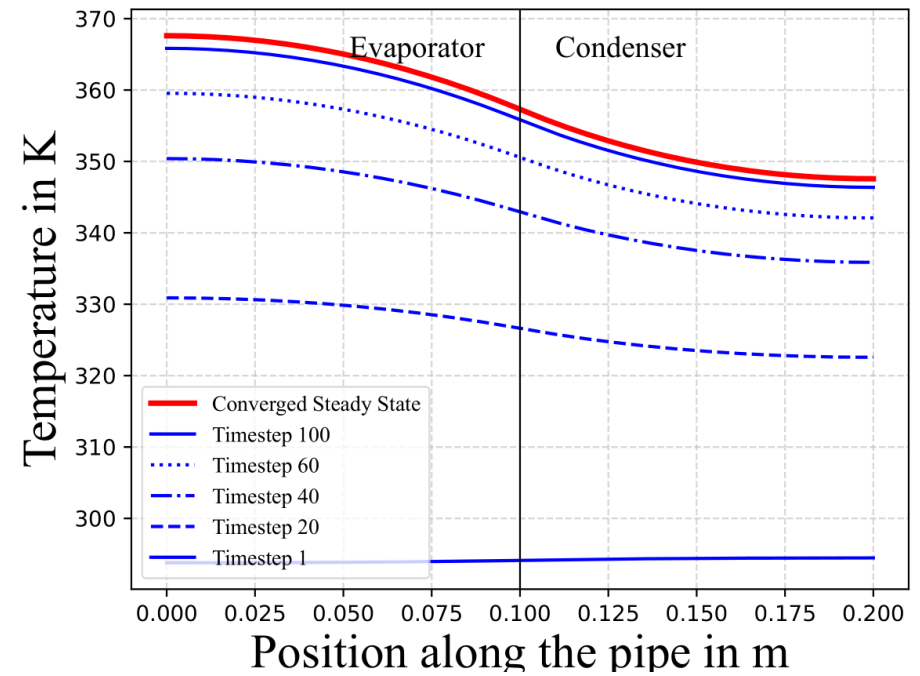
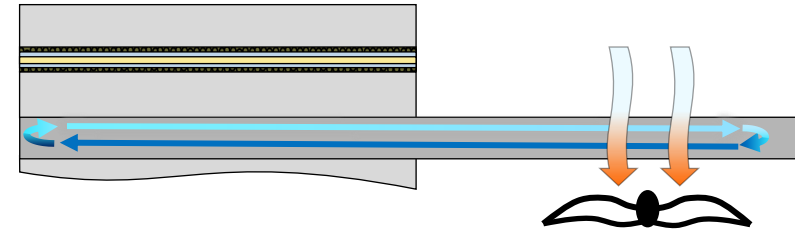


Temperature distribution for $\lambda_{eq}=3300 \text{ W/mK}$; [Kearny et al.]

External air speed $v_{air} = 10 \frac{m}{s}$, $T_{air} = 323.15K$

Results

Temperature distribution along the PHP

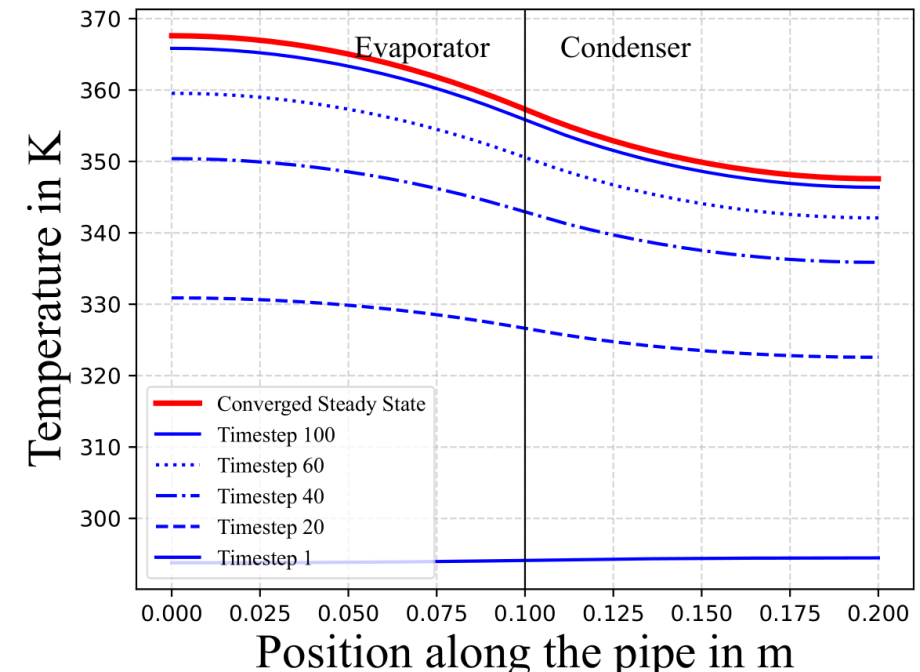


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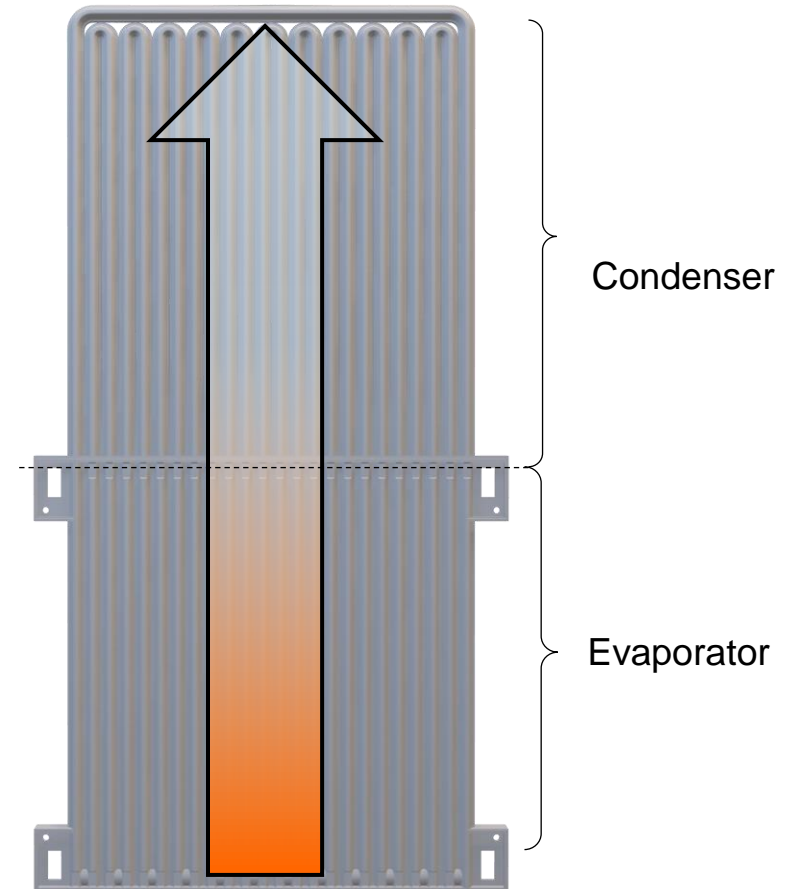
- **Maximum Temperature within Fuel Cell Operation Range;**
- $T_{Ev,max} = 367.7K$
- **Evaporator Temperature Gradient in Pipe Direction $\Delta T_{Ev} = 10.19K$**



Temperature distribution for $\lambda_{eq}=3300$ W/mK [Kearny et al.]
External air speed $v_{air} = 10 \frac{m}{s}$, $T_{air} = 323.15K$

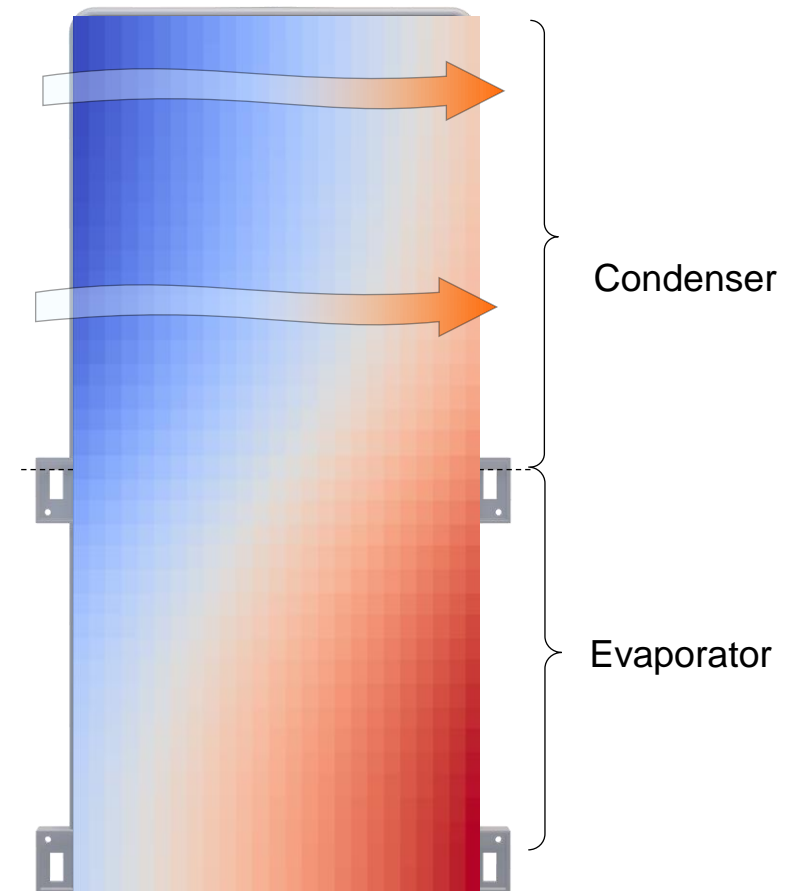
Mitigation of lateral Temperature Gradients

- **Gradient in PHP-Direction**
 - Depends on PHP Performance $\lambda_{eq} > 3400 \text{ W/mK}$



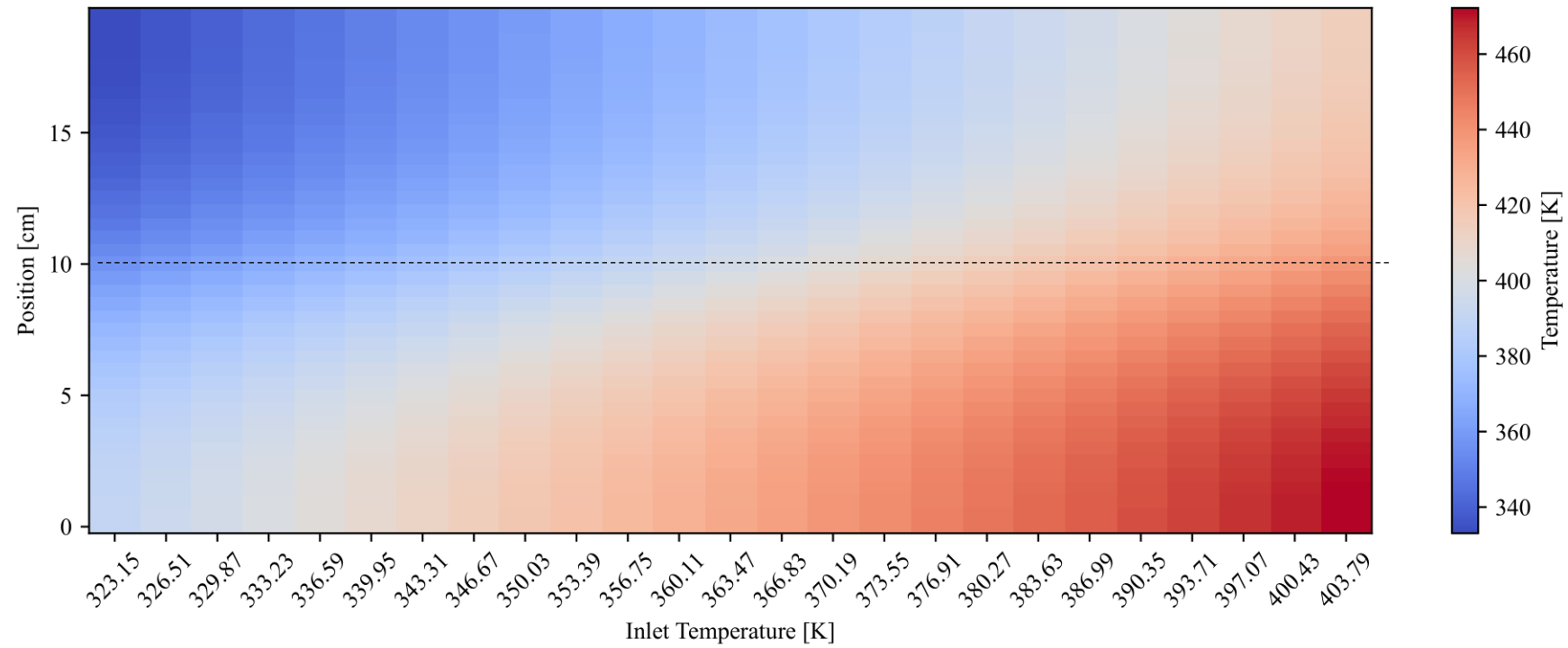
Mitigation of Temperature Gradients

- **Gradient in PHP-Direction**
 - Depends on PHP Performance $\lambda_{eq} > 3400 \text{ W/mK}$
- **Heating of coolant air**
 - Less effective heat transfer in subsequent pipes
 - Temperature gradient in cross-direction



Results

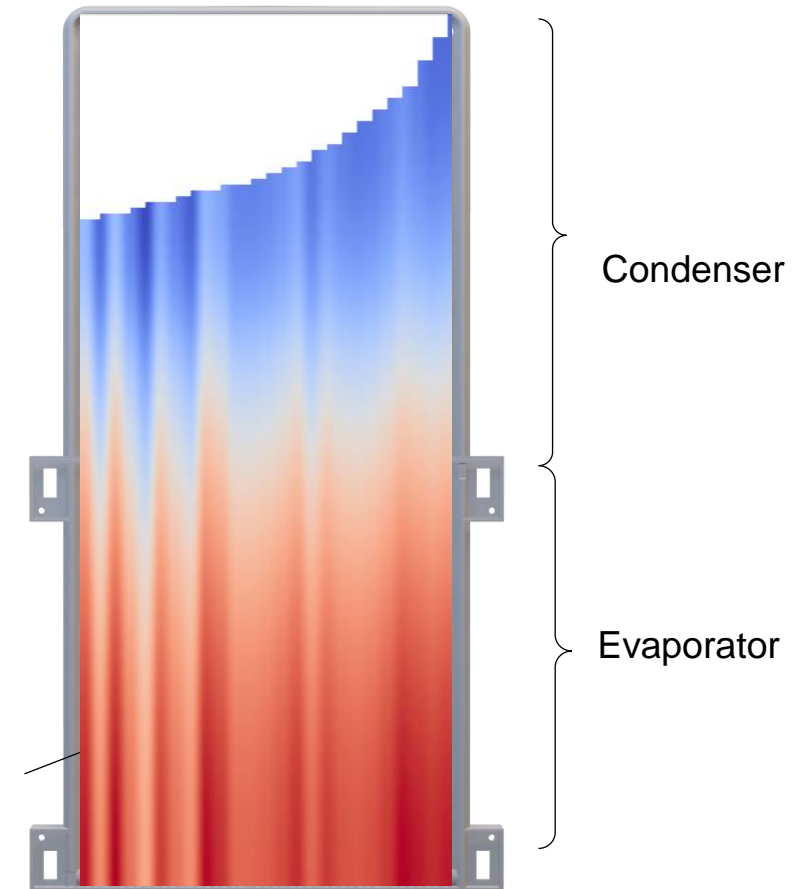
Mitigation of Temperature Gradients



Metigation of Temperature Gradients

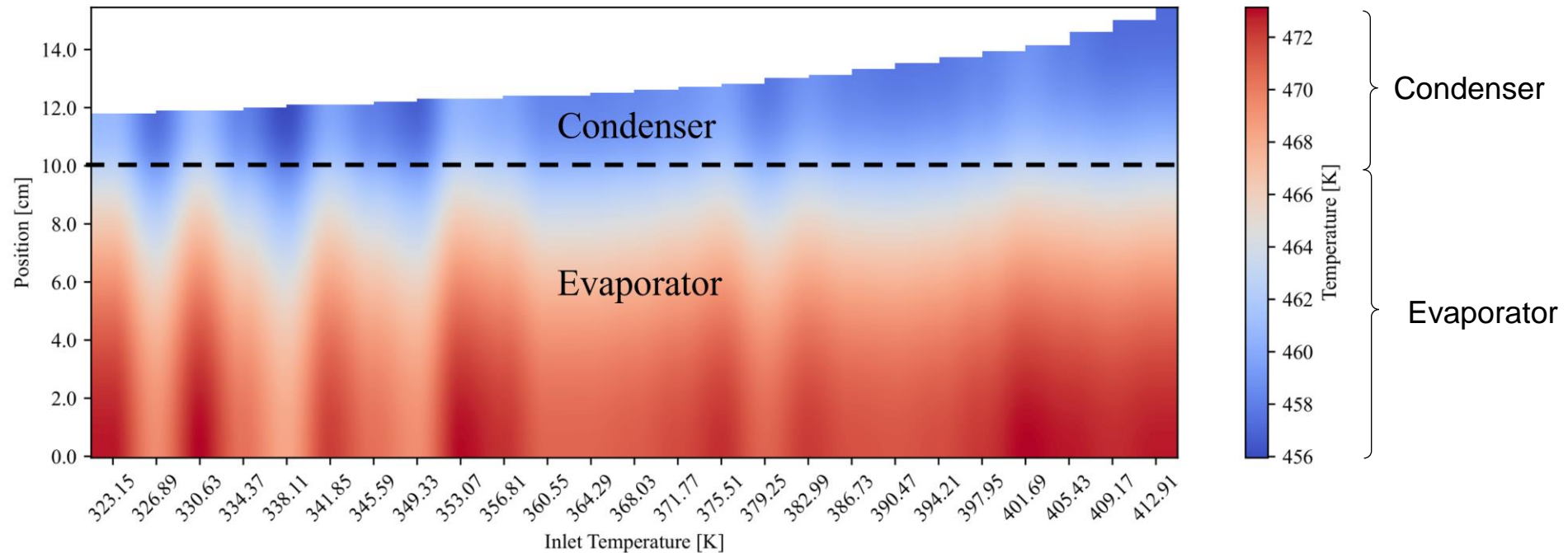
- **Vary condenser lengths**
 - Each single strand must comply with maximum temperature

- **Automated optimization**
 - Closely resembles quadratic growth



Results

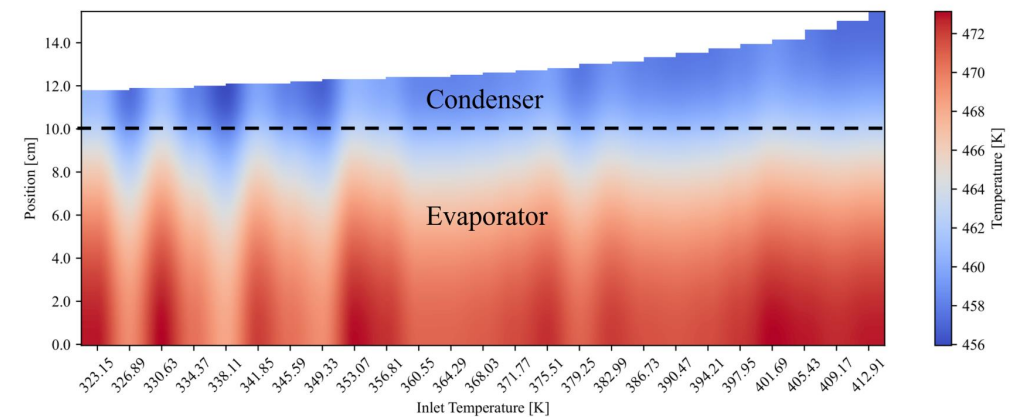
Metigation of Temperature Gradients



Difference between hottest and coldest spot in the Evaporator $\Delta T < 15 K$

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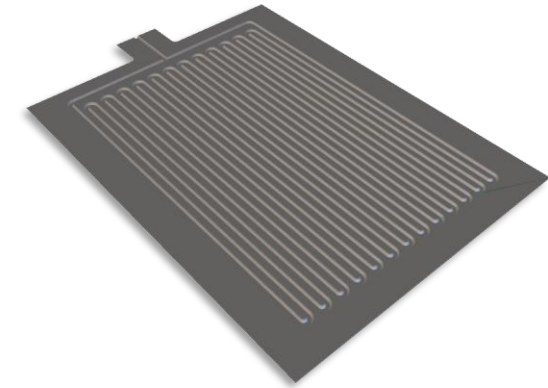


Conclusions



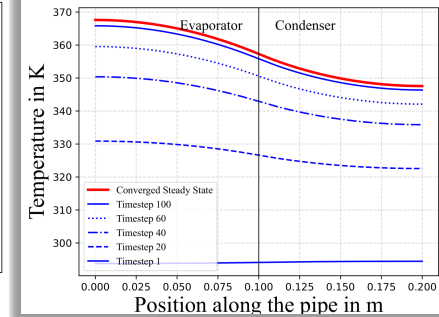
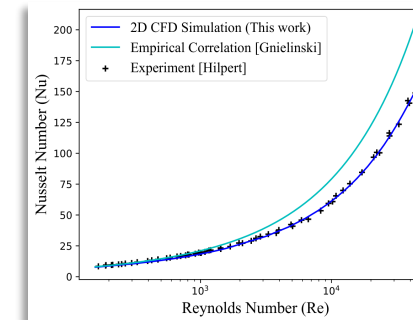
Heat Pipe assisted air cooling for fuel cells

- A new concept to integrate PHP into fuel cells was introduced
- Potential advantages are increased simplicity and efficiency



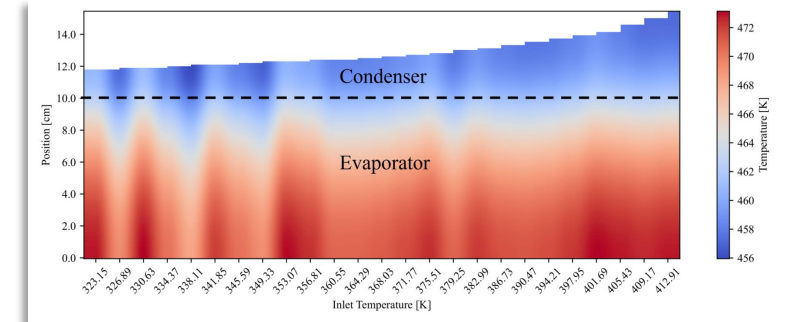
1D Model

- 1D thermal model was implemented and validated
- Temperature distributions along a single pipe were calculated
- Thermal Conditions demonstrate theoretical feasibility for FC cooling



Design Adaptations

- Design adaptations for Mitigation of Temperature Gradients introduced
- Improved temperature homogeneity was achieved



Future Research

Manufacturing of hexagonal PHP

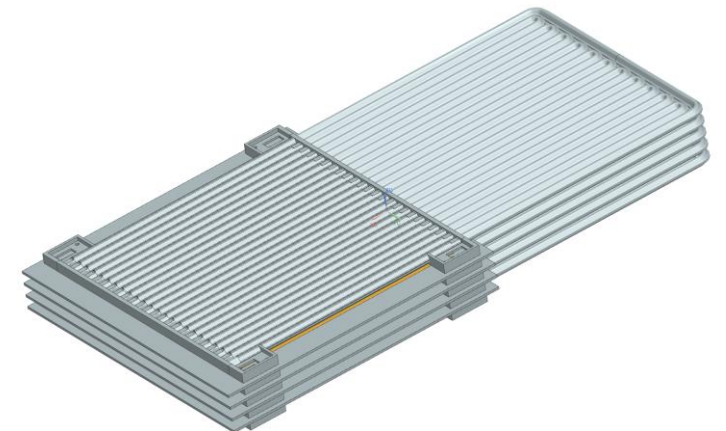
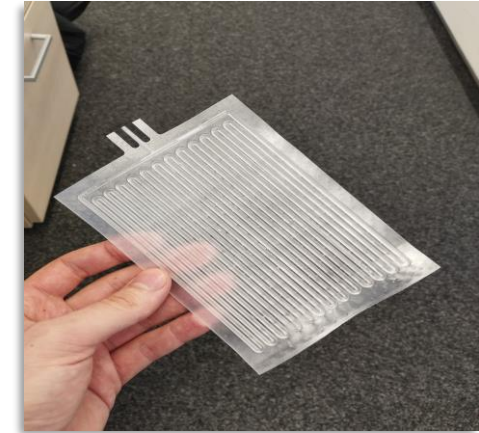
- A prototype will be designed and its design iterated
- Different manufacturing and filling procedures will be evaluated and tested

Testing

- The prototypes will be tested to determine their real thermal performance
- Prototypes, operating conditions and measurement techniques varied

Scaling and integration

- The scaling of the thermal behavior in a complete PHP and a FC Stack will be evaluated
- Impact on fuel cell operation determined and optimized



References



[Burke 2010] - Burke, Kenneth; Colozza, Anthony; Jakupca, Ian Development of passive Fuel cell thermal management heat exchanger: <https://arc.aiaa.org/doi/10.2514/6.2009-4656>

[Supra 2014] - Kühllkonzepte für Hochtemperatur- Polymerelektrolyt-Brennstoffzellen-Stacks:
ISBN 978-3-89336-946-1

[Ayel 2021] - Ayel, Vincent; Slobodeniuk, Maksym; Bertossi, Rémi; Romestant, Cyril; Bertin, Yves: Flat plate pulsating heat pipes: A review on the thermohydraulic principles, thermal performances and open issues; DOI: [10.1016/j.applthermaleng.2021.117200](https://doi.org/10.1016/j.applthermaleng.2021.117200)

[Nikolayev 2021] - Nikolayev, Vadim S.; Physical principles and state-of-the-art of modeling of the pulsating heat pipe: A review; DOI: [10.1016/j.applthermaleng.2021.117111](https://doi.org/10.1016/j.applthermaleng.2021.117111)

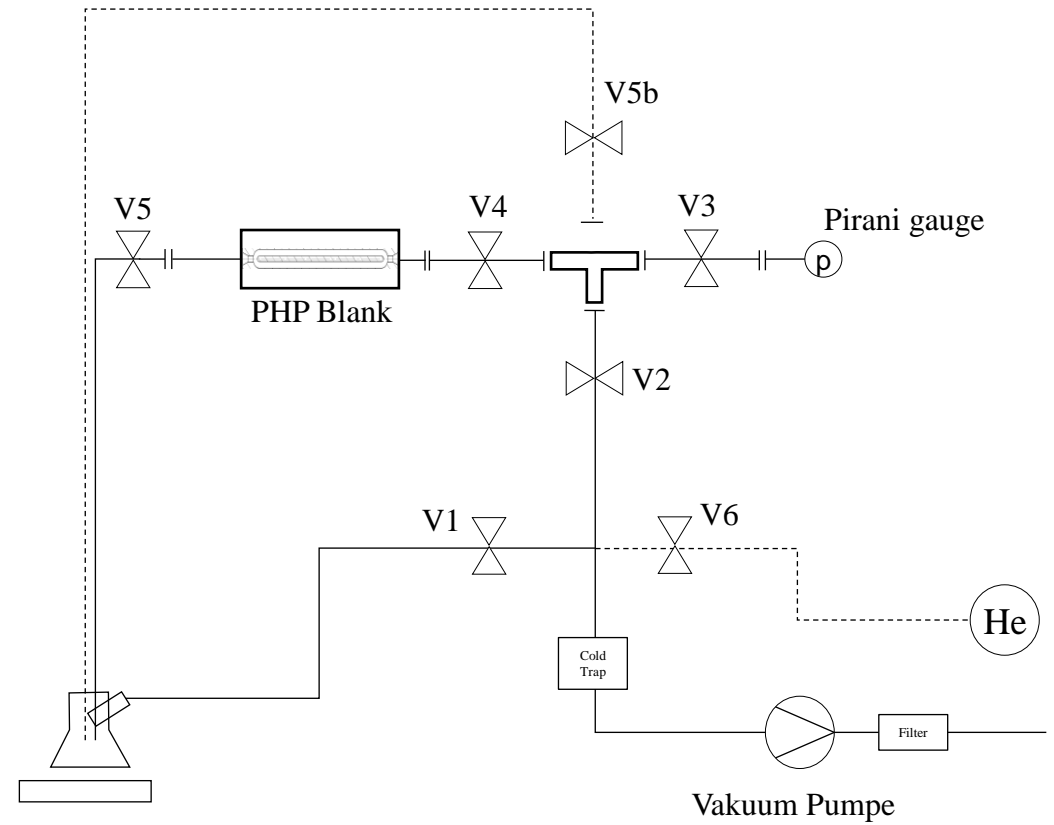
[Hilpert 1933] - Hilpert, R. Wärmeabgabe von geheizten Drähten und Rohren im Luftstrom; DOI [10.1007/BF02719754](https://doi.org/10.1007/BF02719754)

Thank you for listening!

**I am looking forward to feedback and suggestions for my
upcoming research.**

Mail: friedrich.franke@dlr.de

PHP Filling



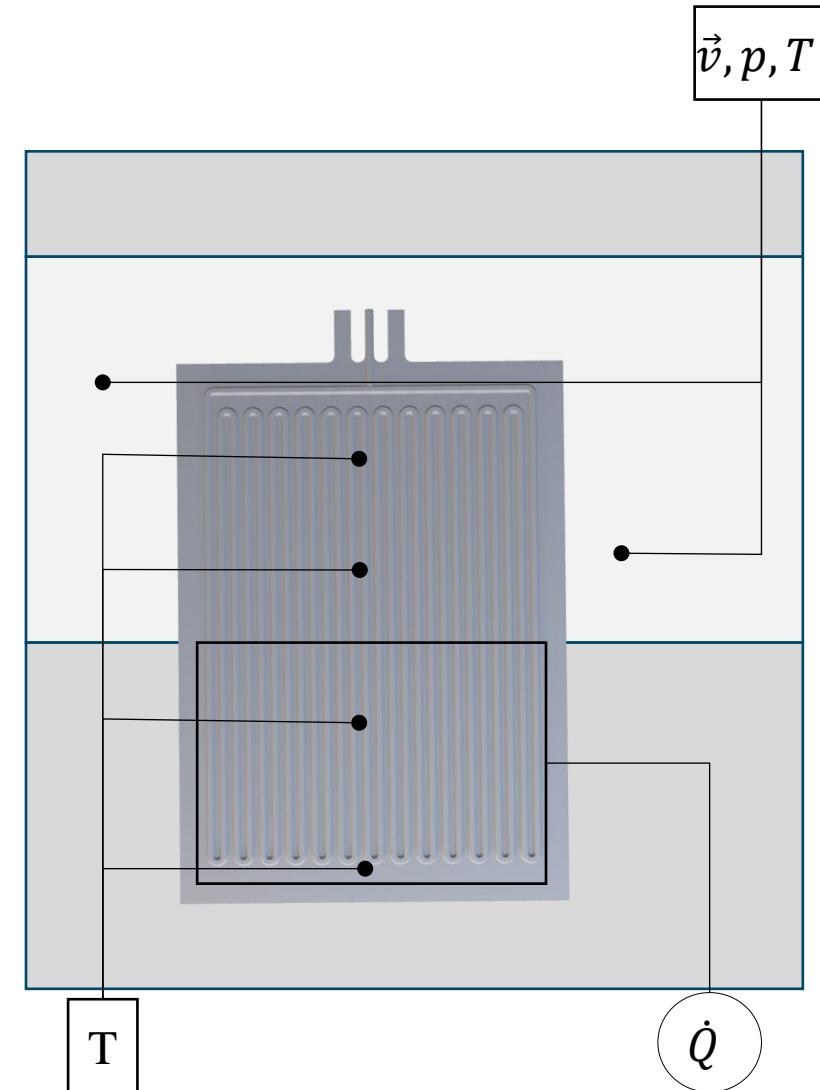
Blank Demonstrator Copper 3D Printing



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



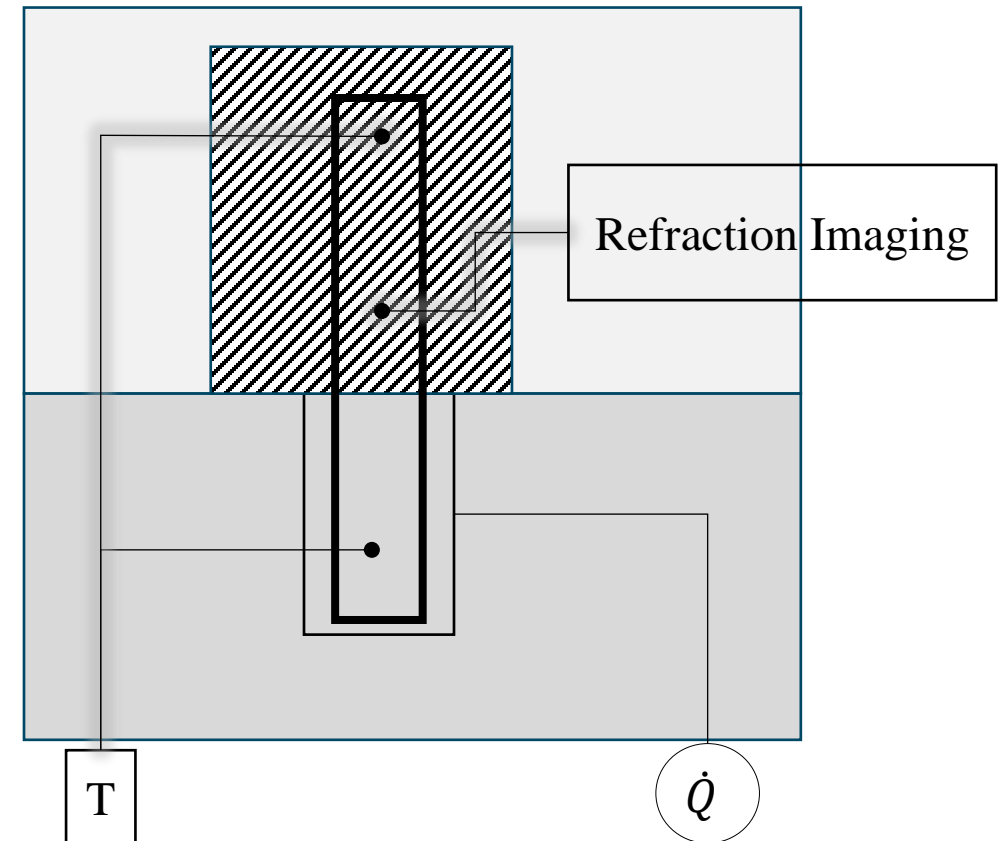
Temperature measure

Heat source

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



Temperature measure

Heat source

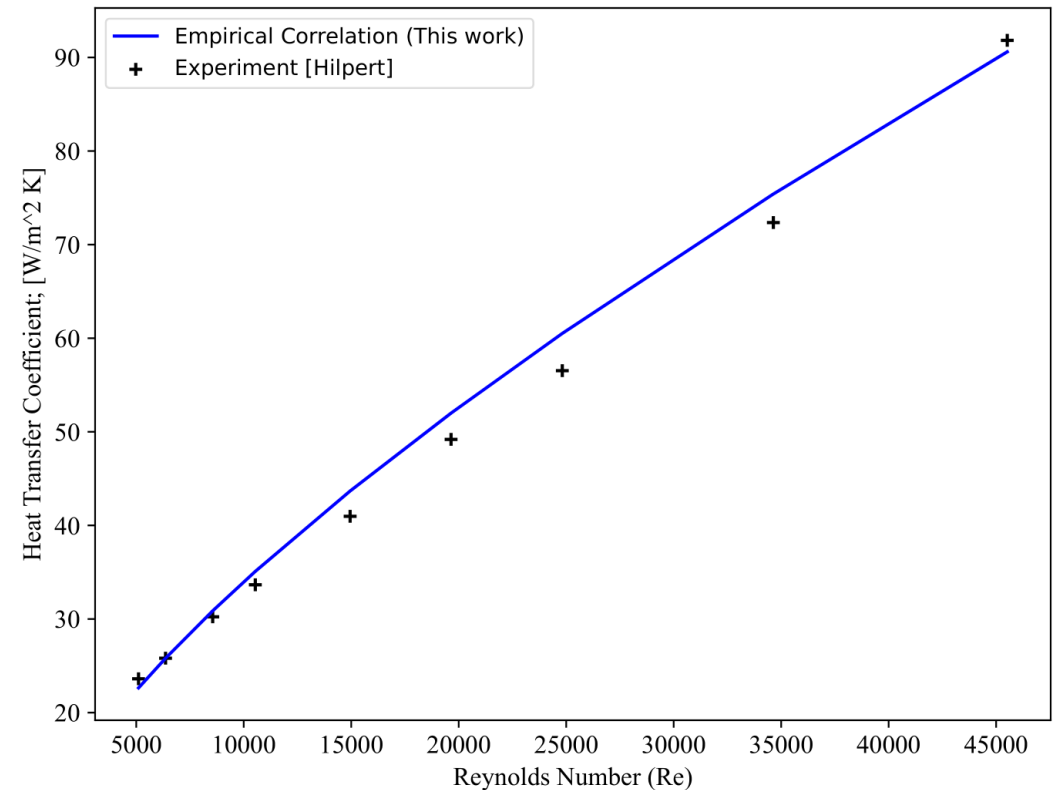
Analytical-empirical Modeling of Convection



Quantification of heat sink

- Calculate heat transfer $\dot{W}_{Air}(\vartheta)$;
 - Empirical correlation based on Gnielinski et al.[1]
 - $Nu_{cb} = 0.3 + \sqrt{Nu_{lam}^2 + Nu_{turb}^2}$
 - Validation with experimental data [2, 3]
 - Calculations alignment closely with measured data

$$\rightarrow \bar{\Delta}_{error} = 3,1\%$$



Comparison of heat transfer with experimental data by *Hilpert et al.* [2]

Difficulties of Modelling PHP Interior



Equivalent thermal conductivity

- **Determine λ_{eq}**
 - **Simulating PHP behaviour is challenging**
 - **Most simulations fail to consider all influences**
- Literature Based approach is chosen *Ayel et al. [4]*

2 Phase
problem

Small scale
cappillary
forces

Wall friction &
wetting

Unclear
vapour state

Boiling,
condensing &
evaporation

Film
deposition
mechanics

Dynamic and
time
dependent

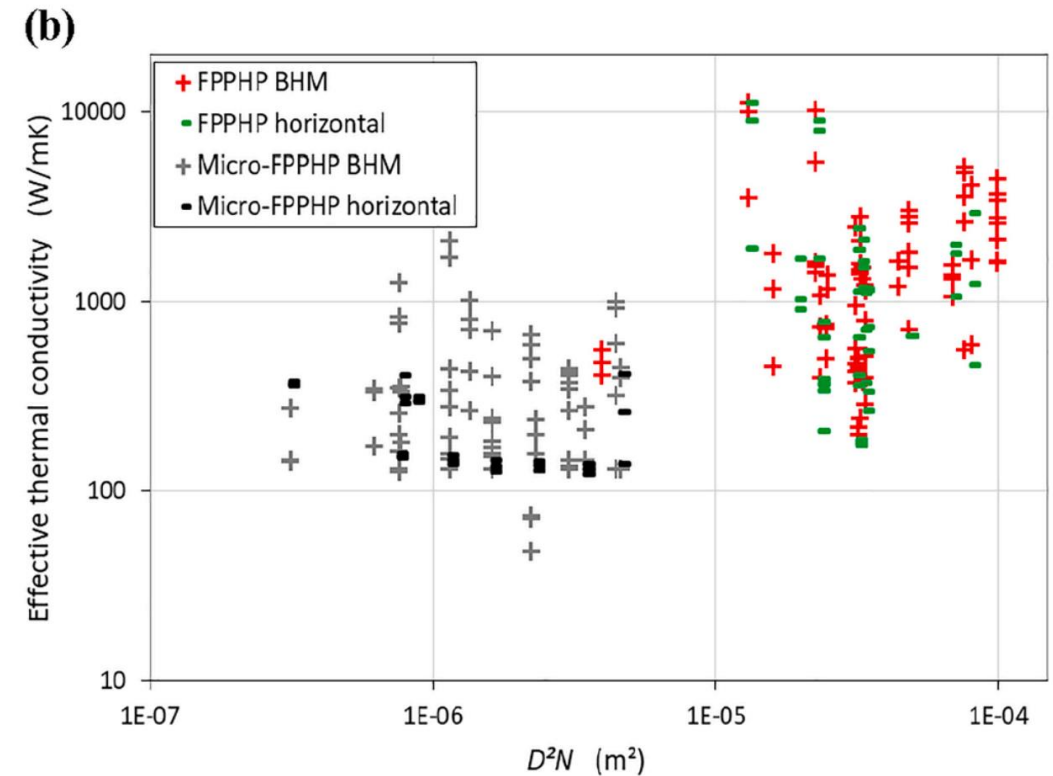
Approximating Thermal Performance

Equivalent thermal conductivity

- **Determine λ_{eq}**
 - **Simulating PHP behavior is challenging**
 - **Most simulations fail to consider many influences**

→ Literature Based approach is chosen *Ayel et al. [4]*
- **Employing λ_{eq} , $\dot{W}_{Air}(\vartheta)$ and implicit finite differences to solve the PDE**

$$\rho c \frac{\vartheta_i^{n+1} - \vartheta_i^n}{\Delta t} = \lambda_{eq} \frac{\vartheta_{i-1}^n - 2\vartheta_i^n + \vartheta_{i+1}^n}{\Delta x^2} + w\Delta x$$



PHP Prüfstand

