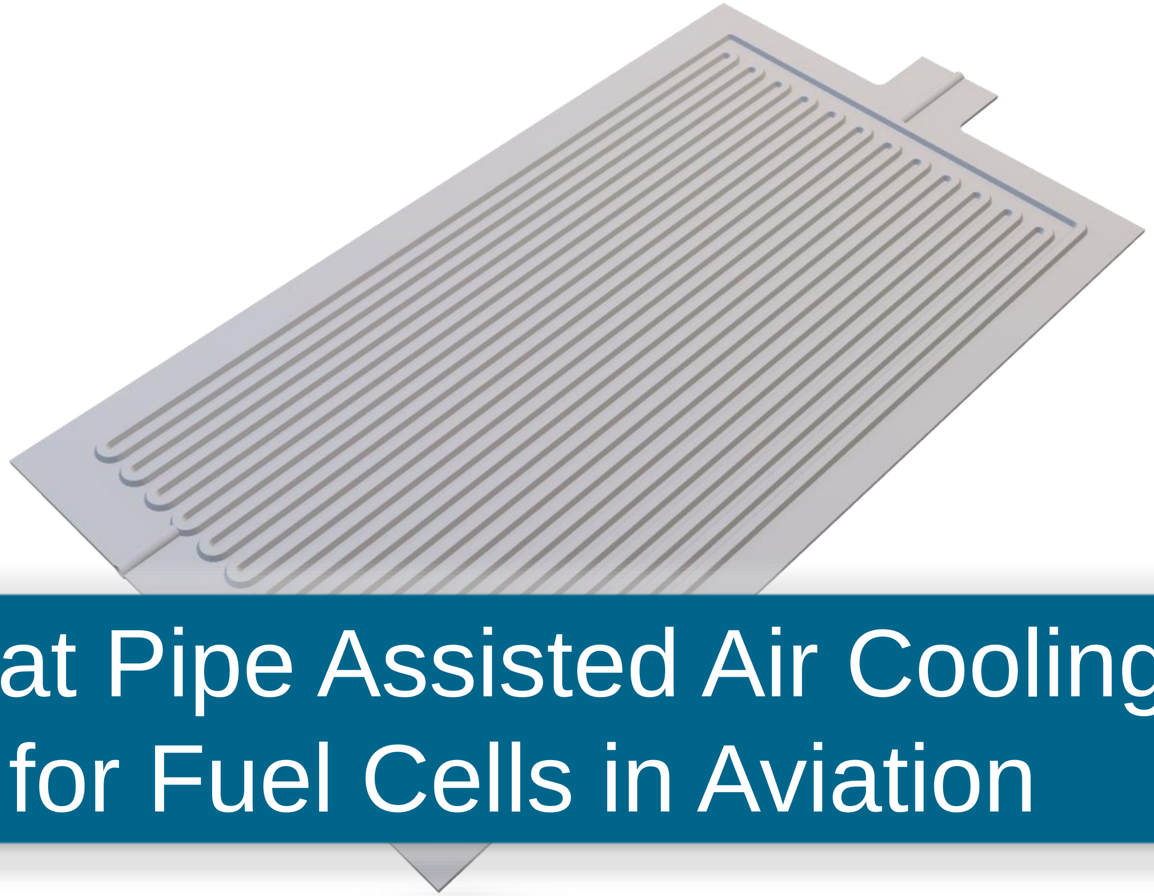
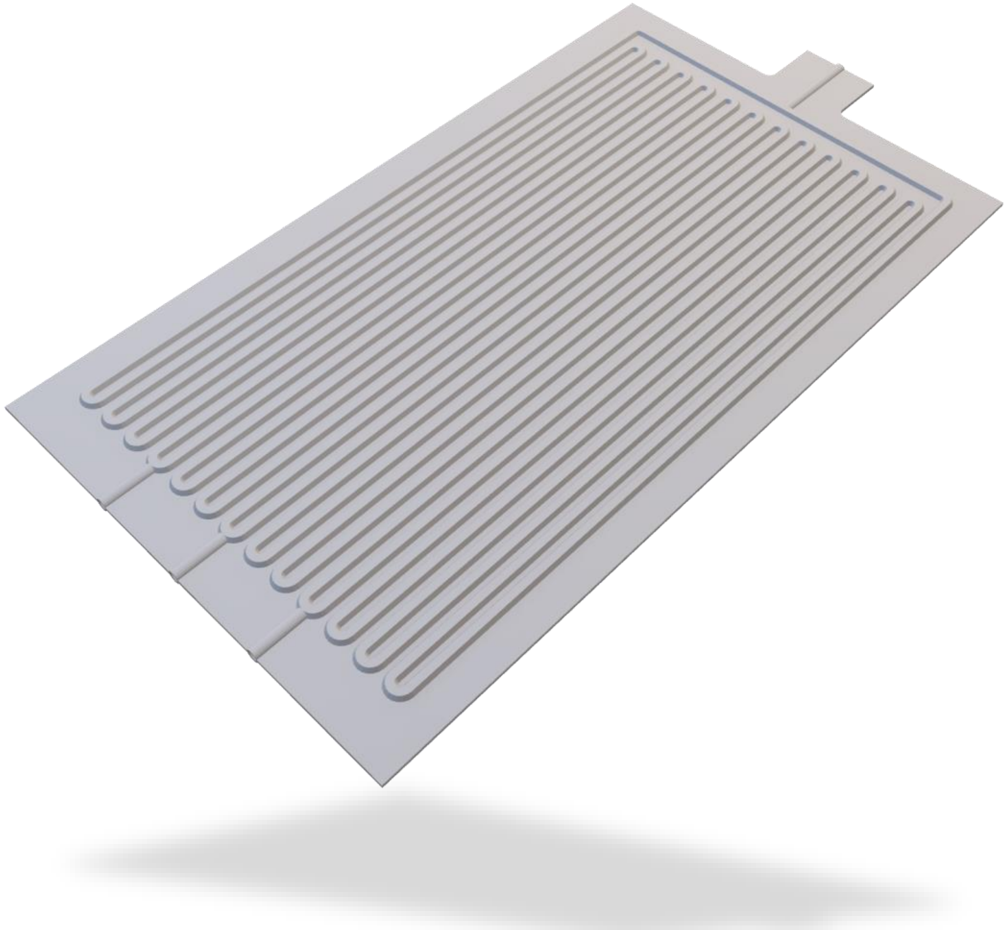


Heat Pipe Assisted Air Cooling for Fuel Cells in Aviation

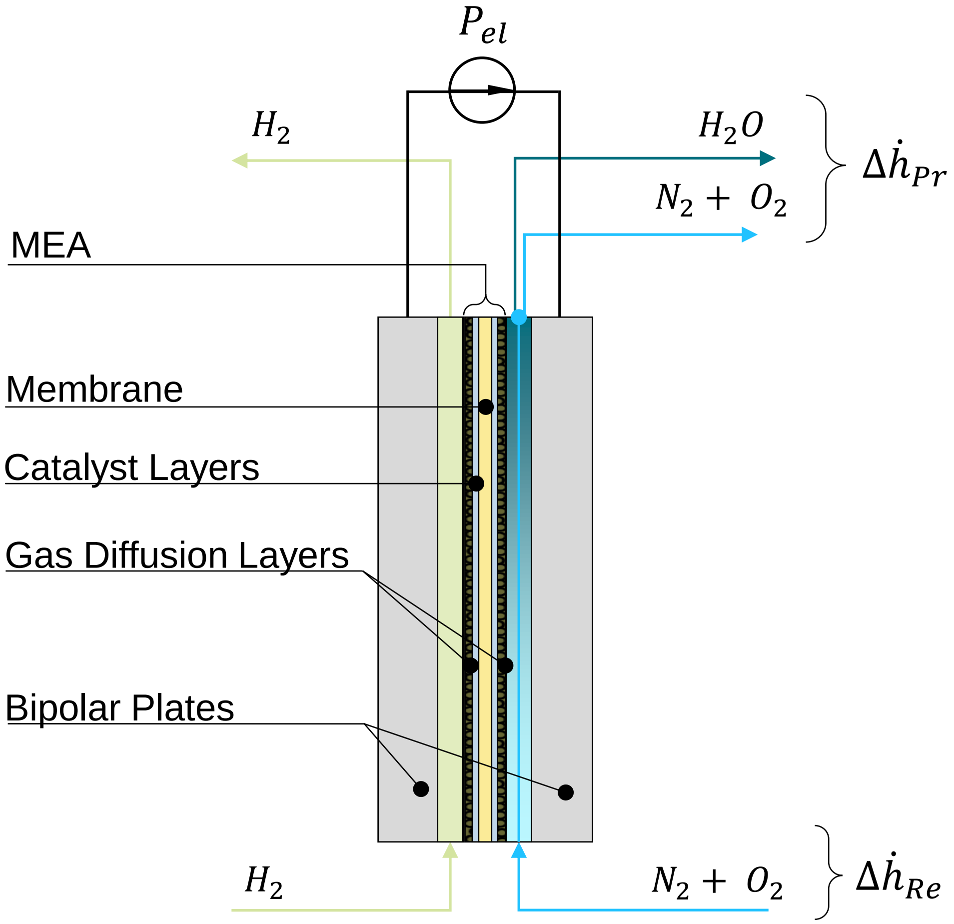
Friedrich Franke | DLR | Madrid 2025

Heat Pipe Assisted Air Cooling for Fuel Cells in Aviation

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

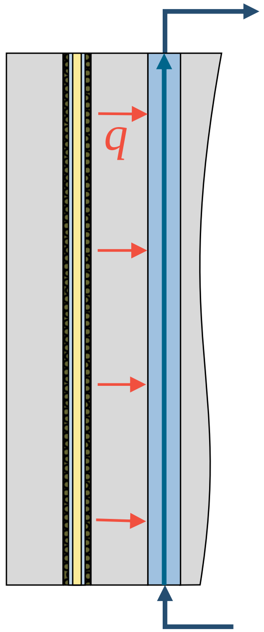


Introduction: Thermal Management for Fuel Cells

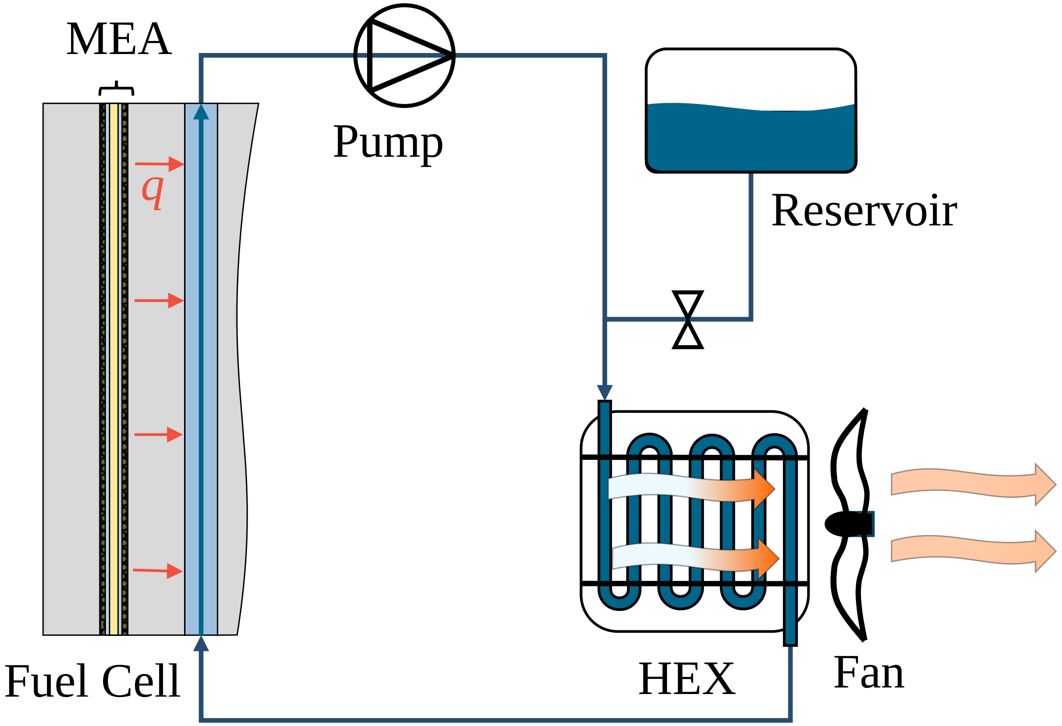


Introduction:
Thermal Management for Fuel Cells

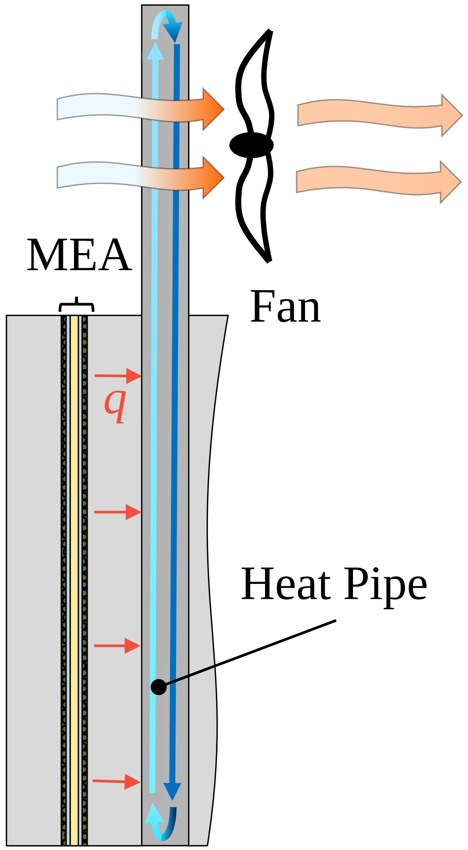
- **$\approx 50\%$ of the Hydrogen‘s energy is converted into heat in the catalyst layer**
- **Heat needs to be absorbed and rejected to the environment**
- **State of the art: Liquid cooling channels are installed in the bipolar plates**



Thermal Management for Fuel Cells

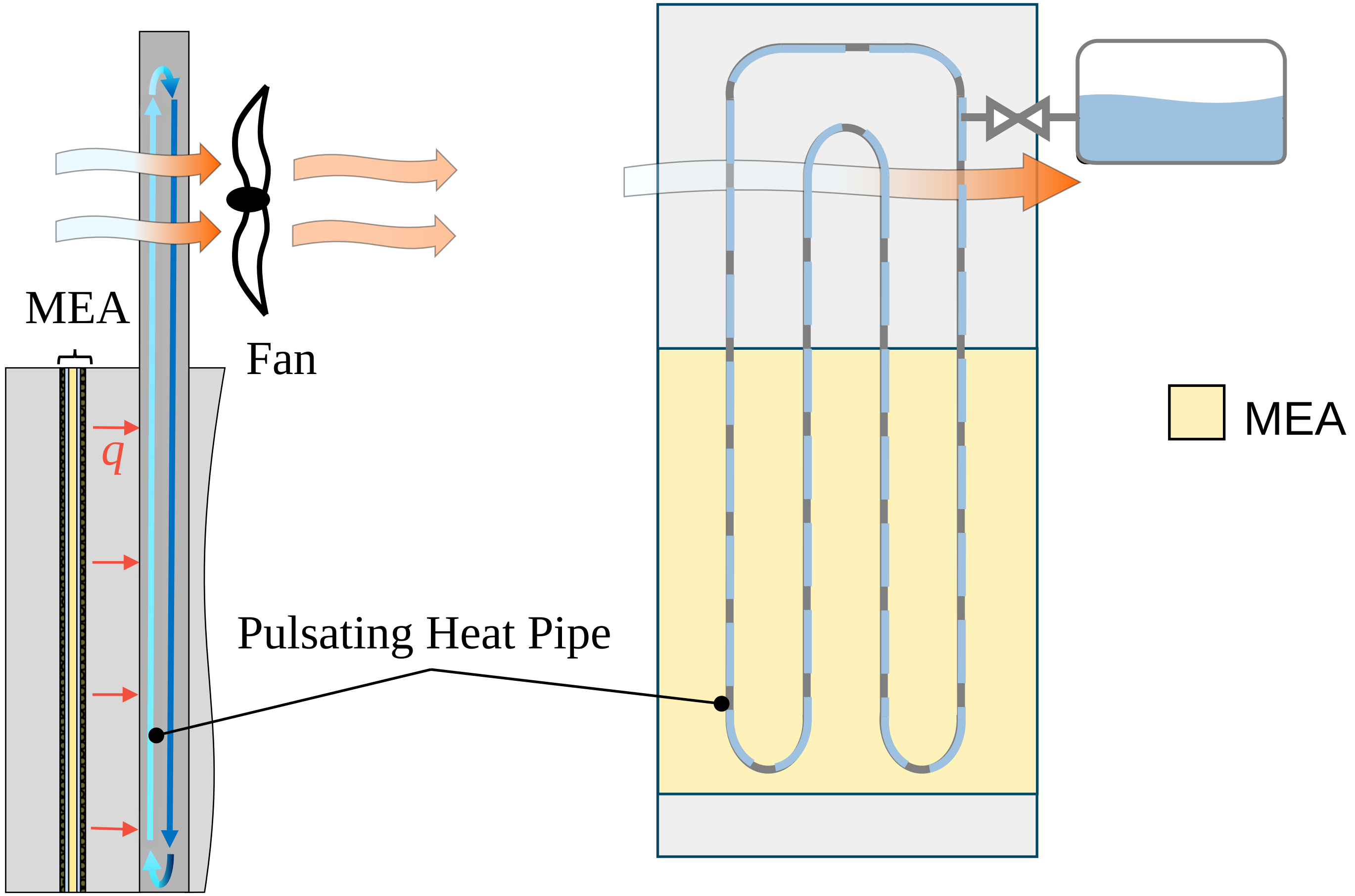


(a) Liquid cooling system

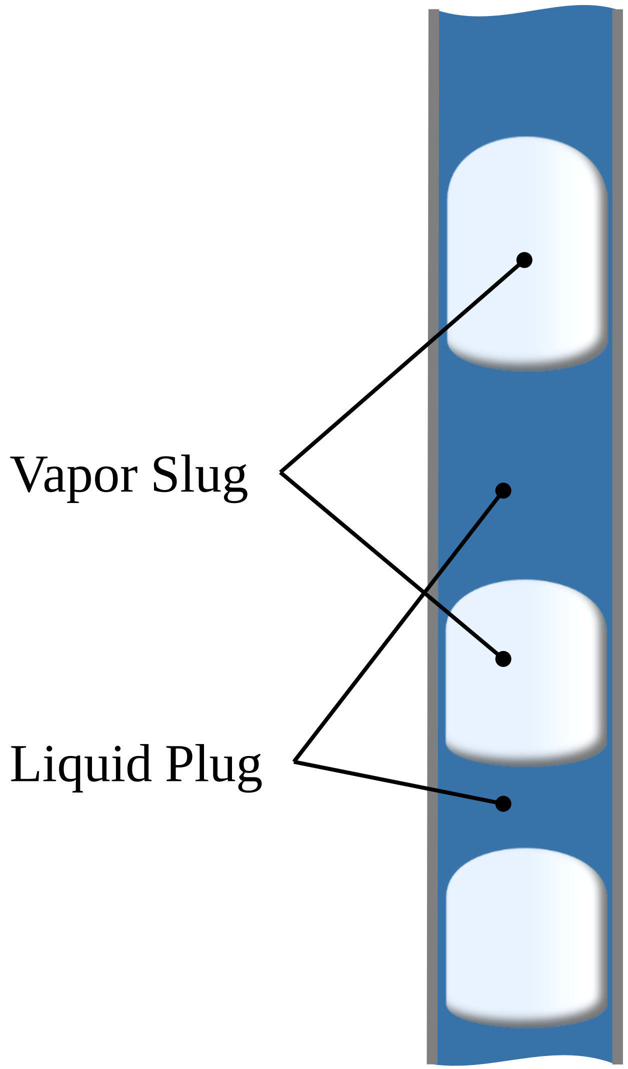


(b) Heat pipe assisted air cooling
[Supra 2014, Burke 2010]

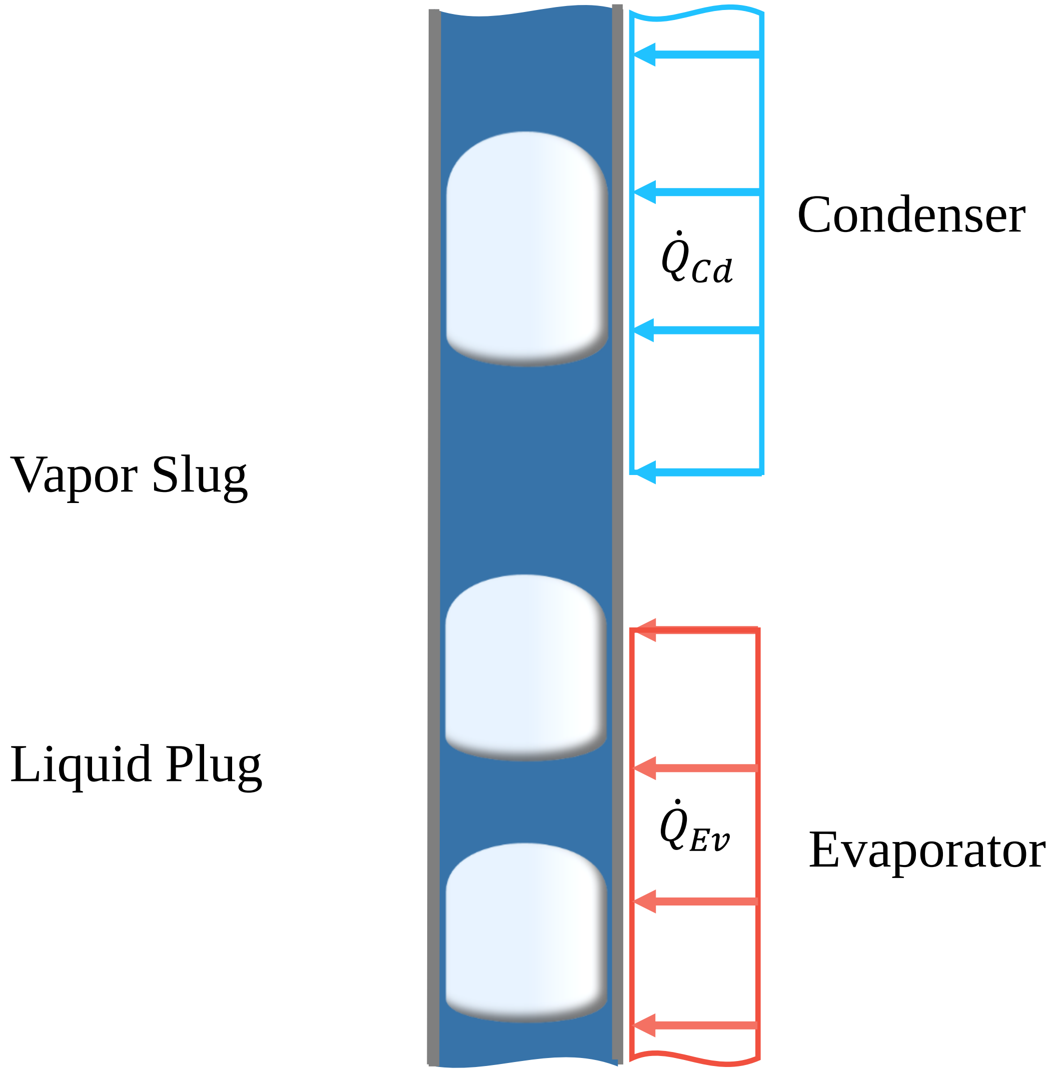
Pulsating Heat Pipe (PHP) Integration



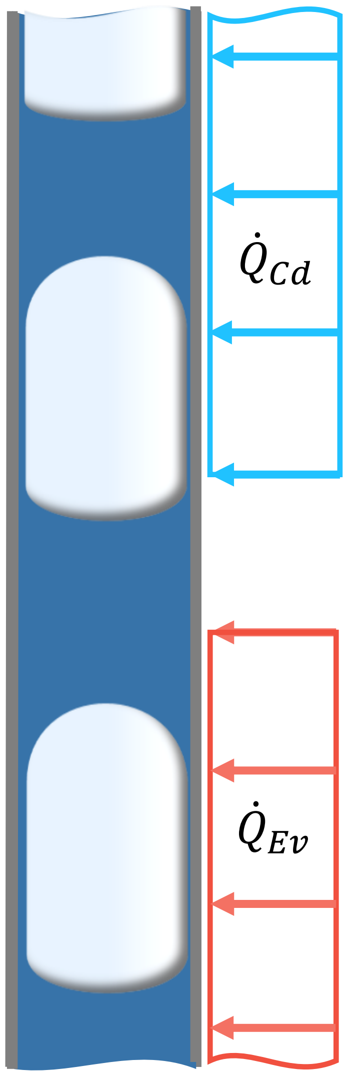
PHP Working Principle



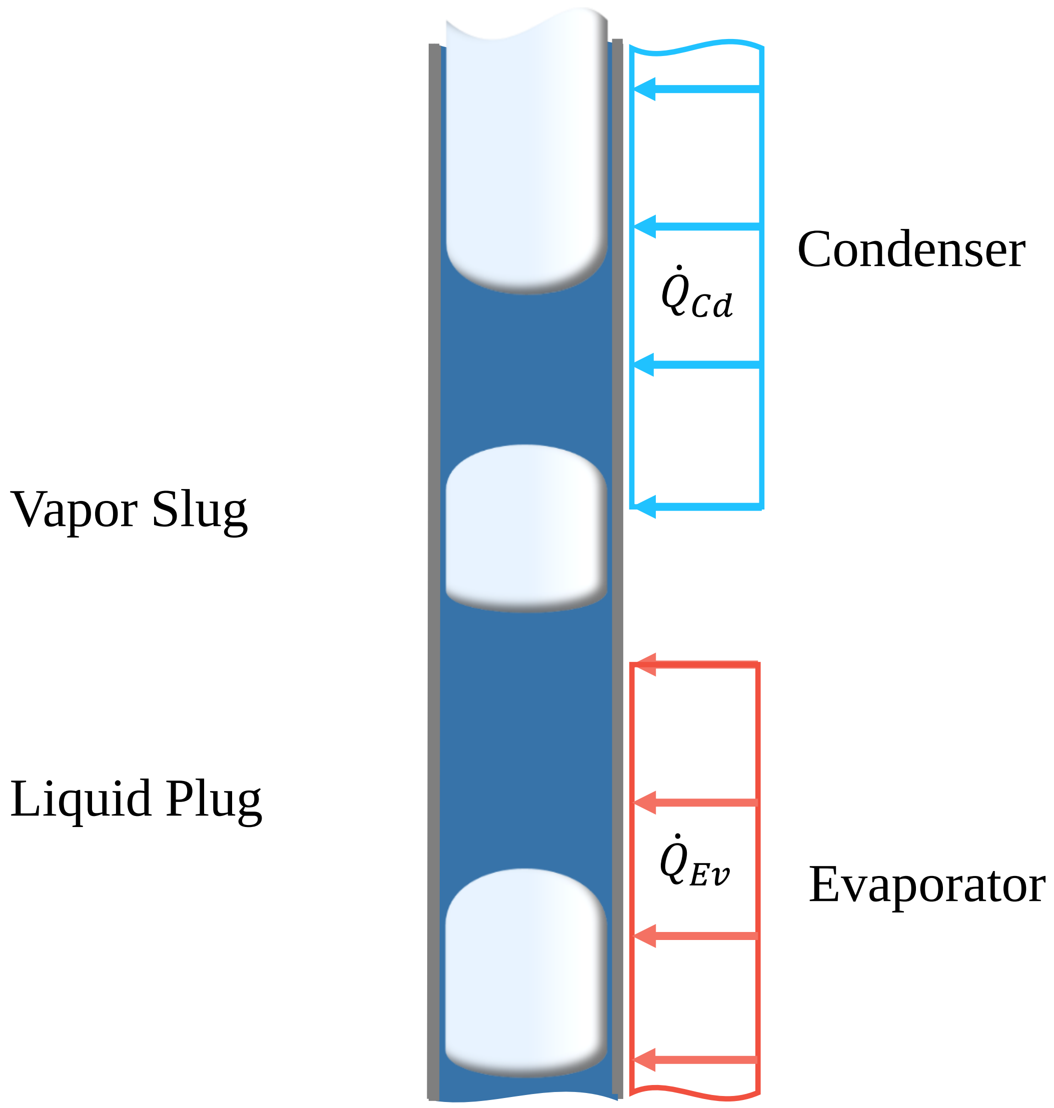
PHP Working Principle



PHP Working Principle

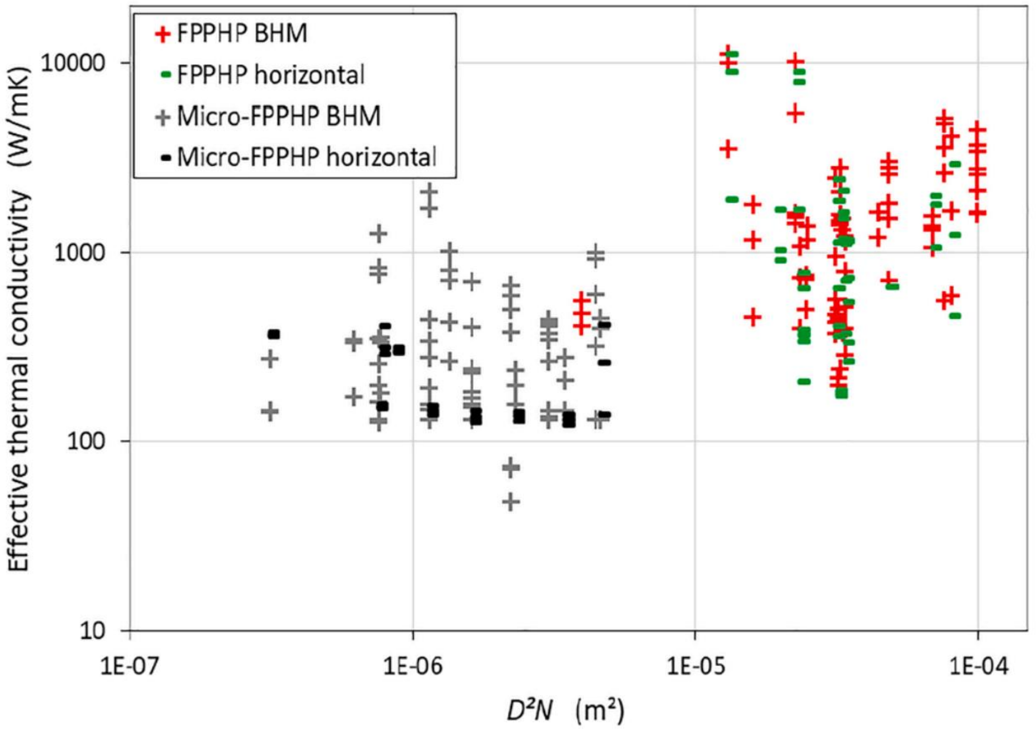


PHP Working Principle



State of Research in PHPs

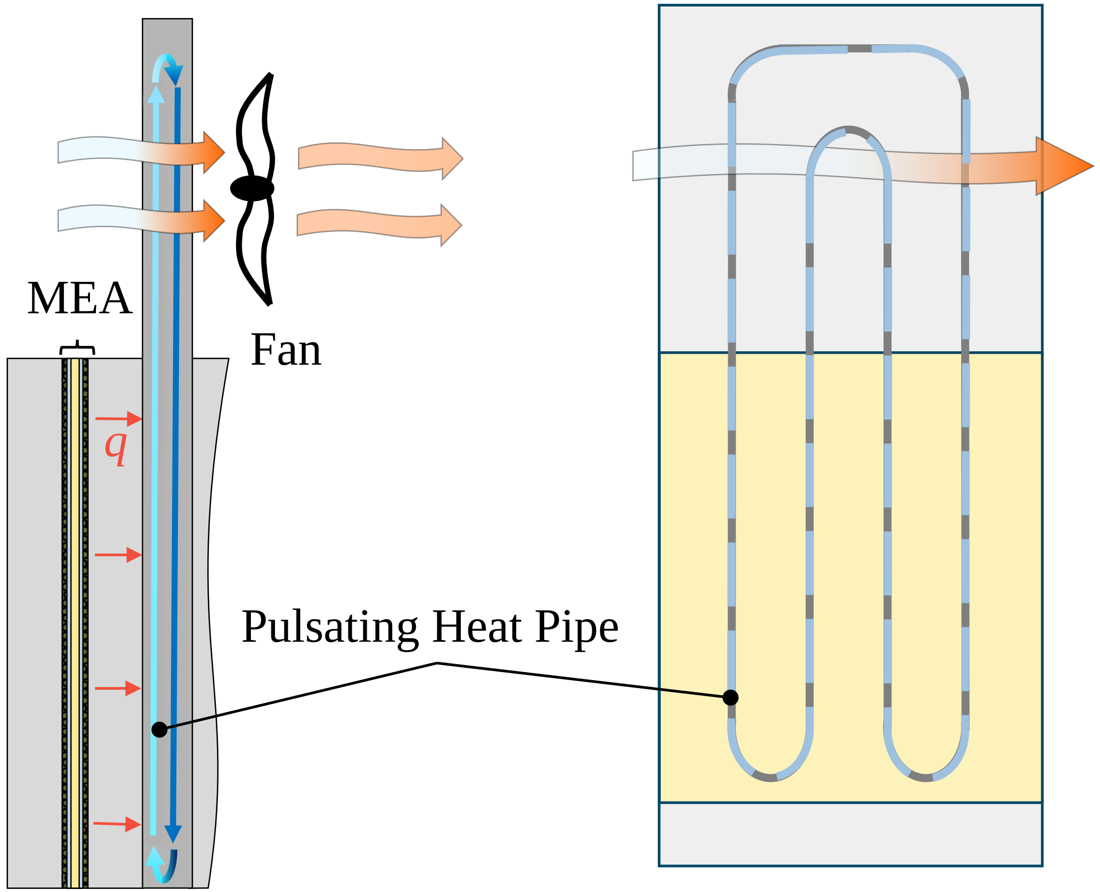
- **Research into circular and rectangular PHPs**
- **Application in cooling of electronics**
- **Large variation in thermal performances** *[Ayel 2021]*
- **Simulation of internal behavior remains challenging** *[Nikolayev 2021]*



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

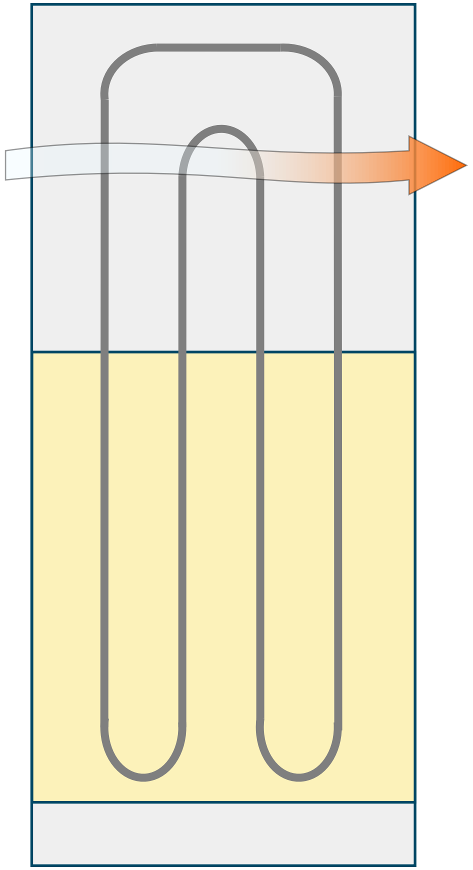
Heat Pipe Assisted Air Cooling for Fuel Cells in Aviation

- Introduction
- Motivation & State of the Art
- **Methodology**
  - **Development of a Thermal Model**
  - **Determine Feasibility for Fuel Cell TMS**
- Results
- Conclusion & Outlook



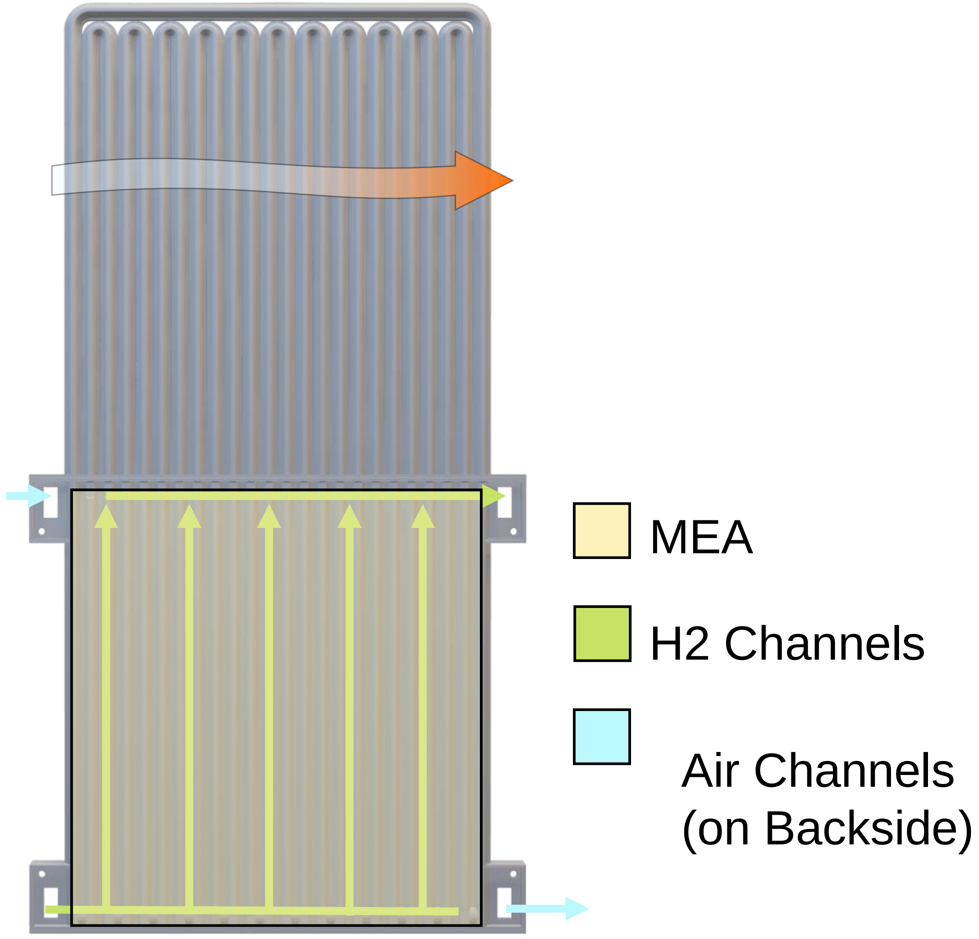
Development of a Thermal Model

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



Development of a Thermal Model

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



Development of a Thermal Model

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

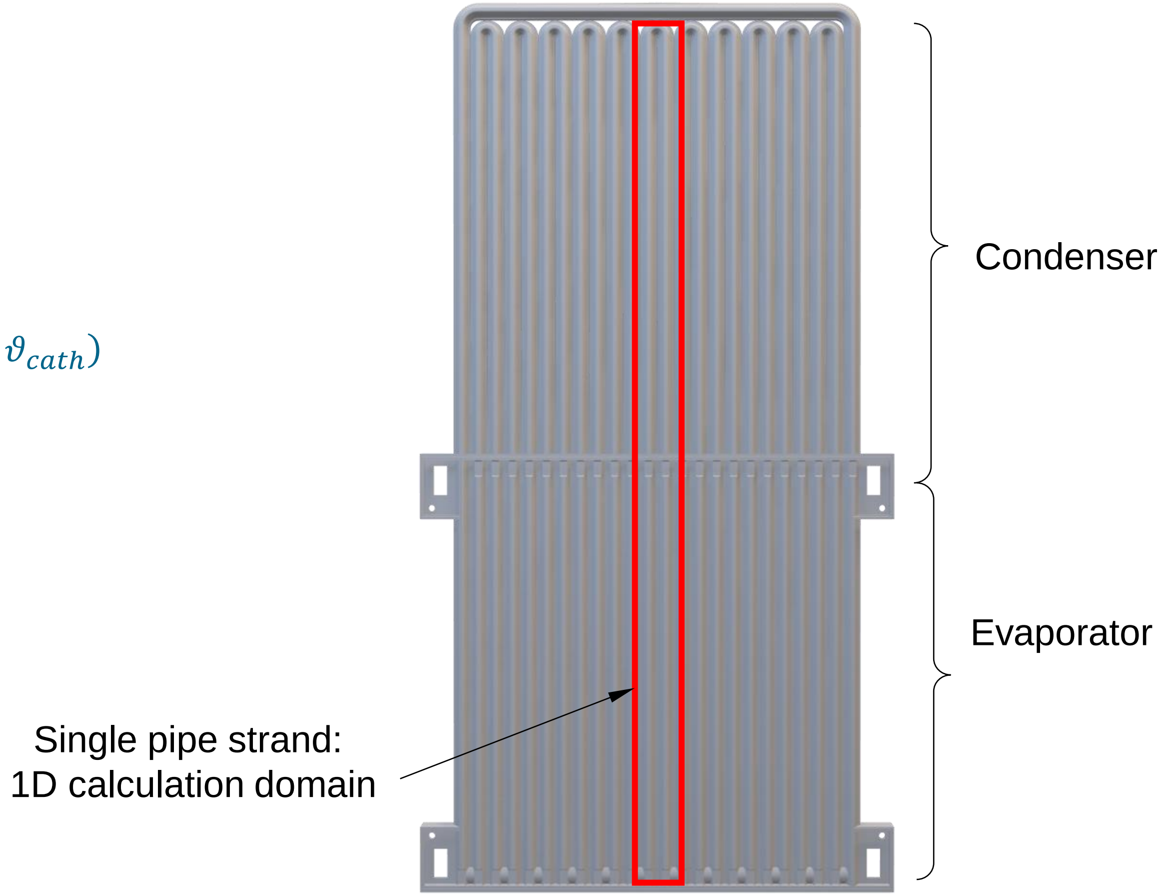
- **1D-Simplificatoin**

Evaporator

$$c\varrho \frac{\partial\vartheta}{\partial t} = \lambda_{eq}\,\nabla^2\vartheta + \dot{W}_{MEA} + \dot{W}_{H2}(\vartheta - \vartheta_{H2}) + \dot{W}_{cath}(\vartheta - \vartheta_{cath})$$

Condenser

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



Development of a Thermal Model

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

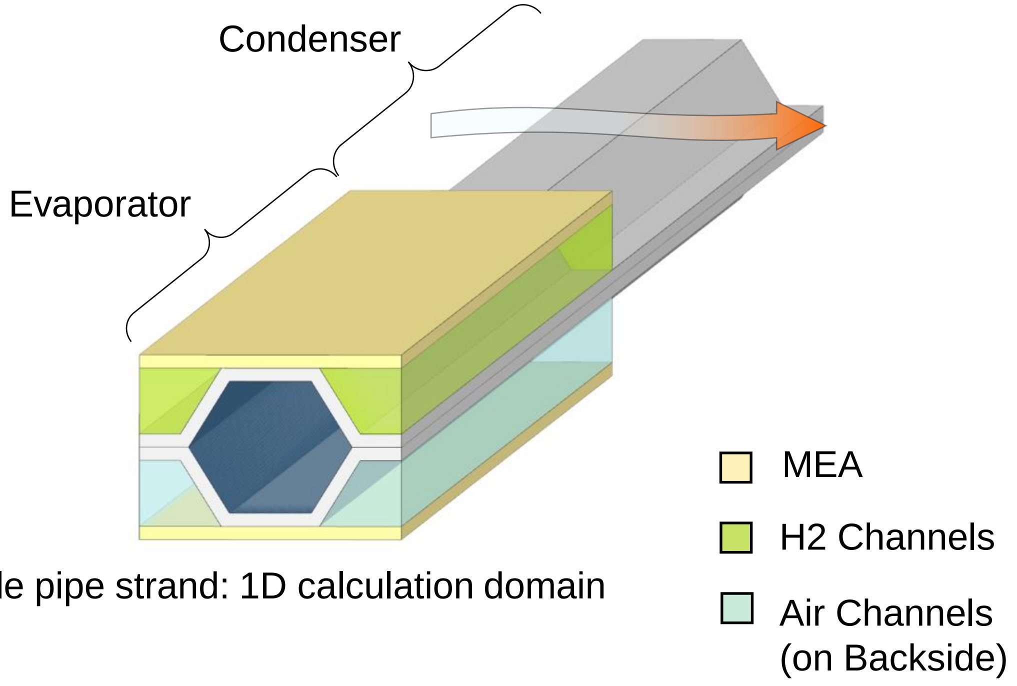
- **1D-Simplification**

Evaporator

$$c\varrho\frac{\partial\vartheta}{\partial t} = \lambda_{eq}\,\nabla^2\vartheta + \dot{W}_{MEA} + \dot{W}_{H2}(\vartheta - \vartheta_{H2}) + \dot{W}_{cath}(\vartheta - \vartheta_{cath})$$

Condenser

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



Single pipe strand: 1D calculation domain

Development of a Thermal Model

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

- **1D-Simplification**

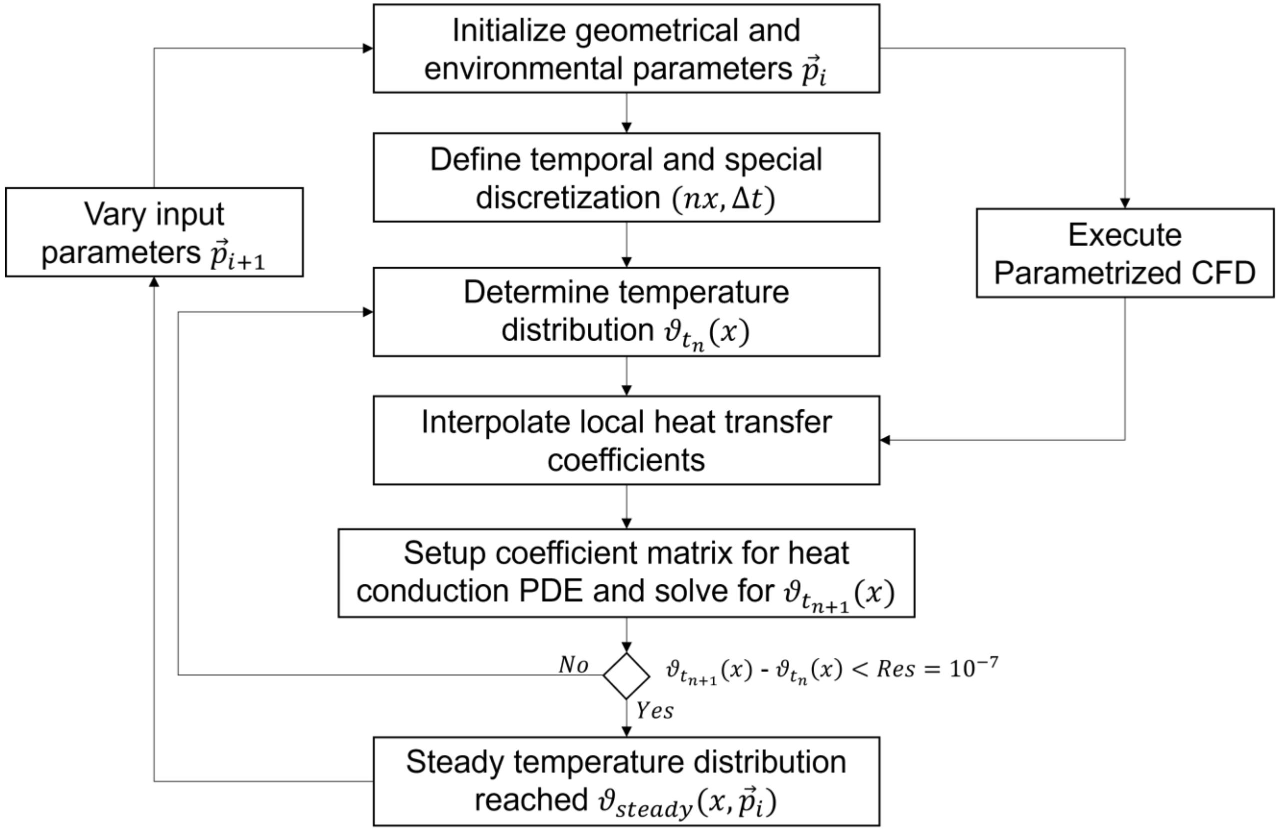
  Evaporator

  $$c\varrho \frac{\partial \vartheta}{\partial t} = \lambda_{eq} \nabla^2 \vartheta + \dot{W}_{MEA} + \dot{W}_{H2} + \dot{W}_{cath}$$

  Condenser

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

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



Development of a Thermal Model

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

- **1D-Simplificatoin**

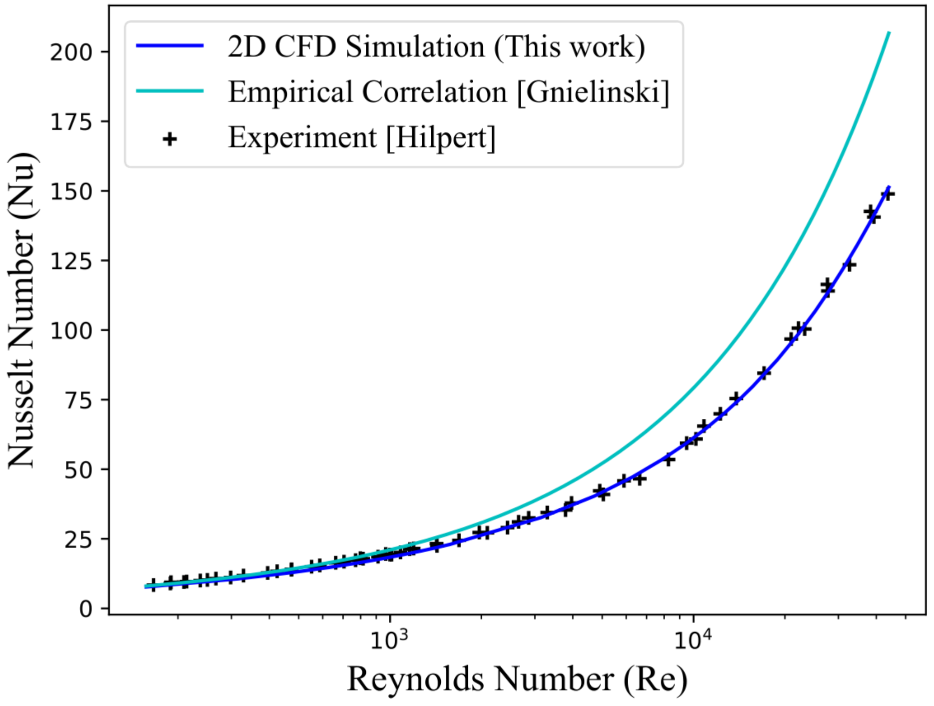
  Evaporator

  $$c\varrho \frac{\partial \vartheta}{\partial t} = \lambda_{eq} \nabla^2 \vartheta + \dot{W}_{MEA} + \dot{W}_{H2} + \dot{W}_{cath}$$

  Condenser

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

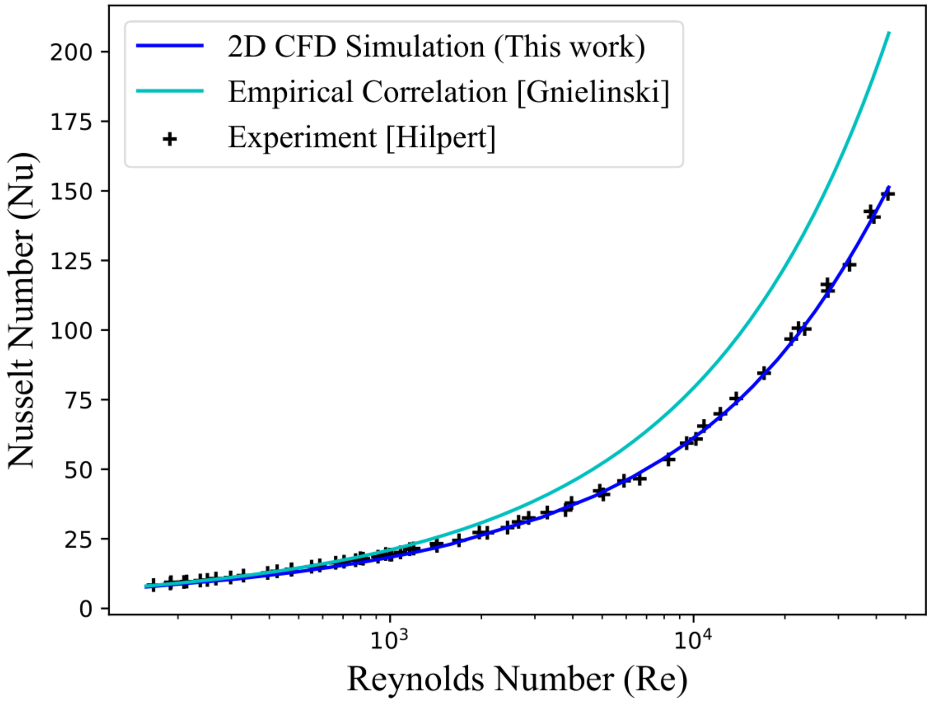
- **Calculation of Convective Heat Transfer via CFD**



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

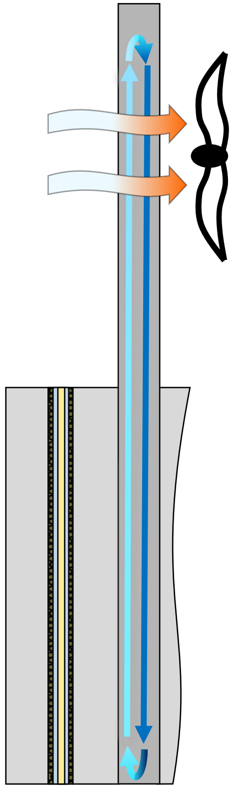
Heat Pipe Assisted Air Cooling for Fuel Cells in Aviation

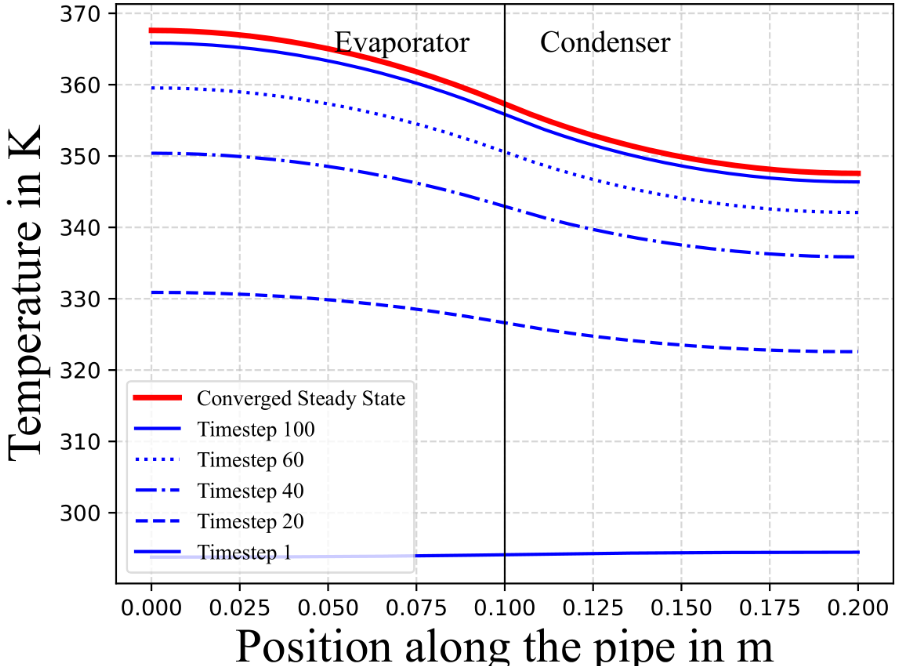
- Introduction
- Motivation & State of the Art
- Methodology
  - Development of a Thermal Model
  - Determine Feasibility for Fuel Cell TMS
- **Results**
  - **Temperature Distribution**
  - **Design Modification**
- Conclusion & Outlook



Results

Temperature distribution along the PHP



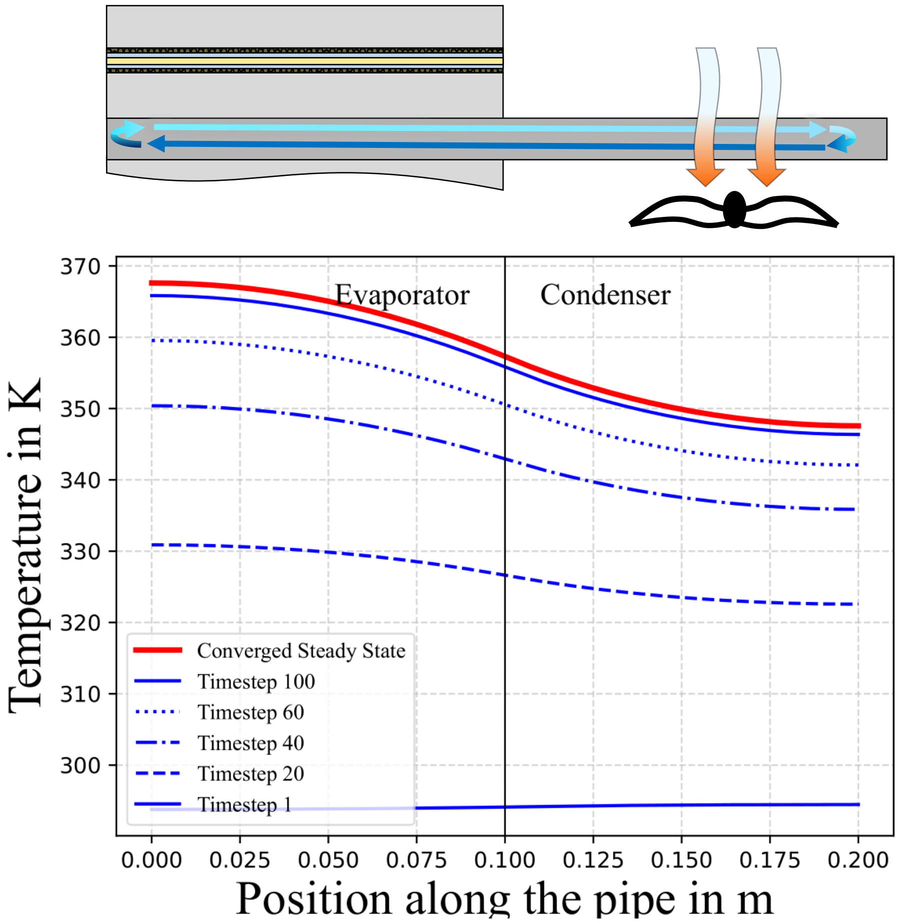


Temperature distribution for λ_{eq}=3300 W/mK; [Kearny et al.]

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

Results

Temperature distribution along the PHP



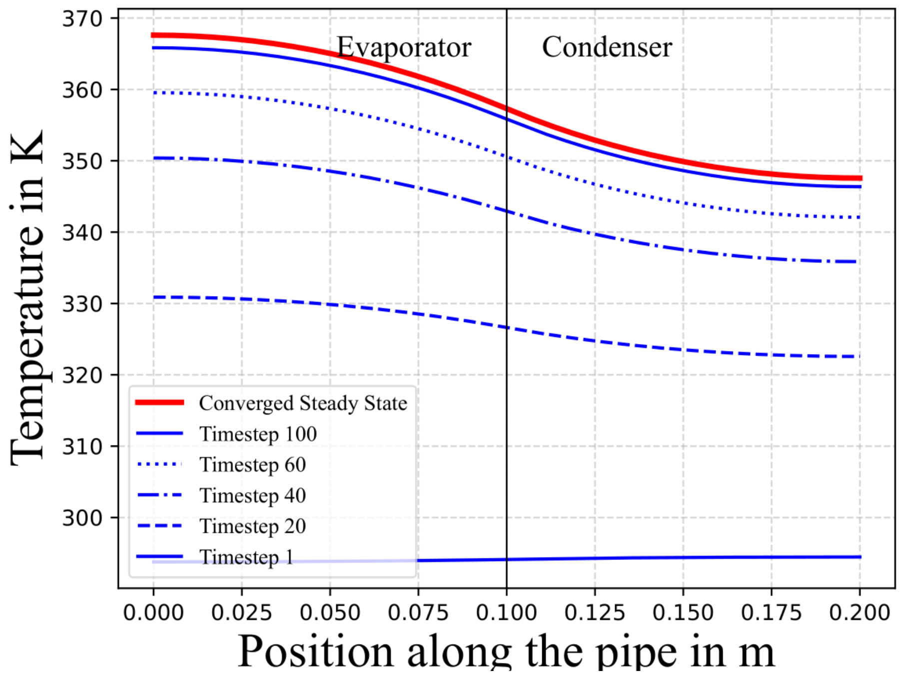
Temperature distribution for λ_{eq}=3300 W/mK; [Kearny et al.]

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

Results

Temperature distribution along the PHP

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

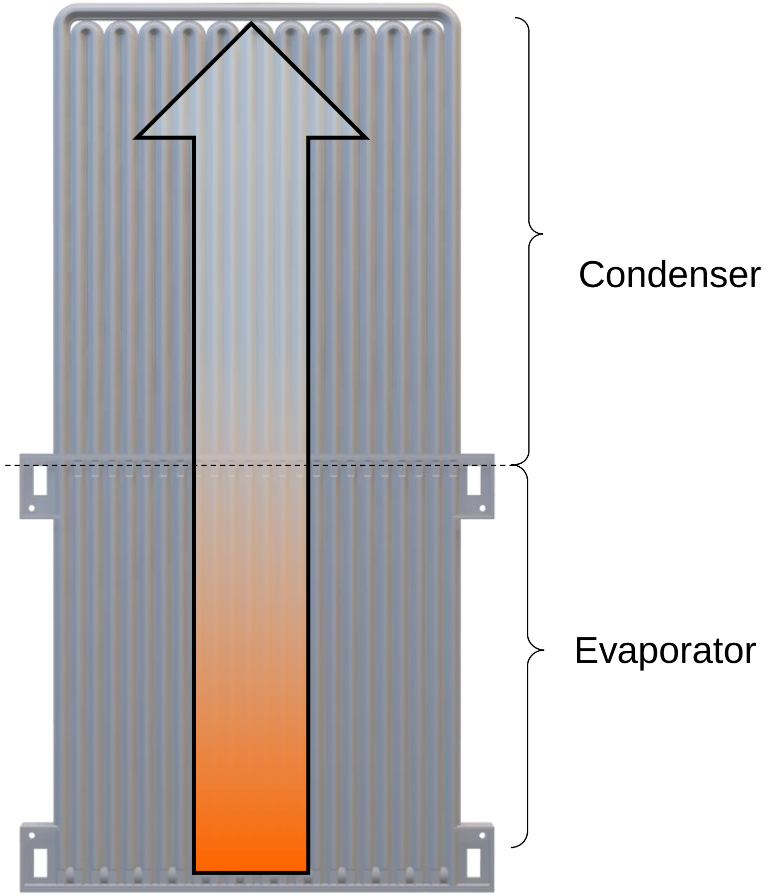


Temperature distribution for λ_{eq}=3300 W/mK [Kearny et al.]
External air speed $v_{air} = 10\frac{m}{s}$, $T_{air} = 323.15K$

Results

Mitigation of lateralTemperature Gradients

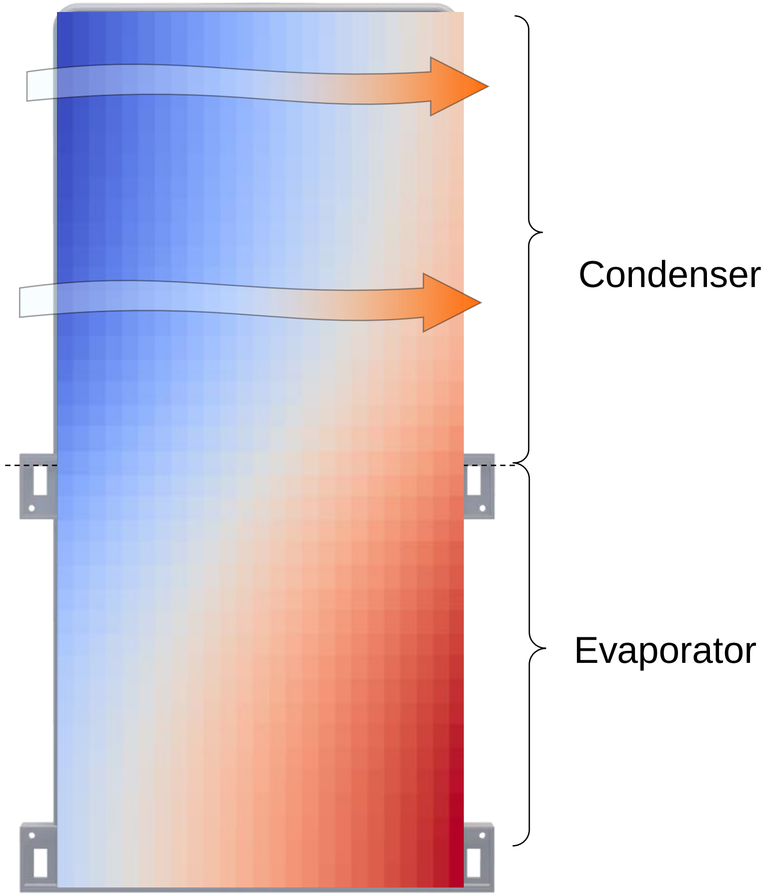
- **Gradient in PHP-Direction**
  - **Depends on PHP Performance $\lambda_{eq} > 3400\ W/mK$**



Results

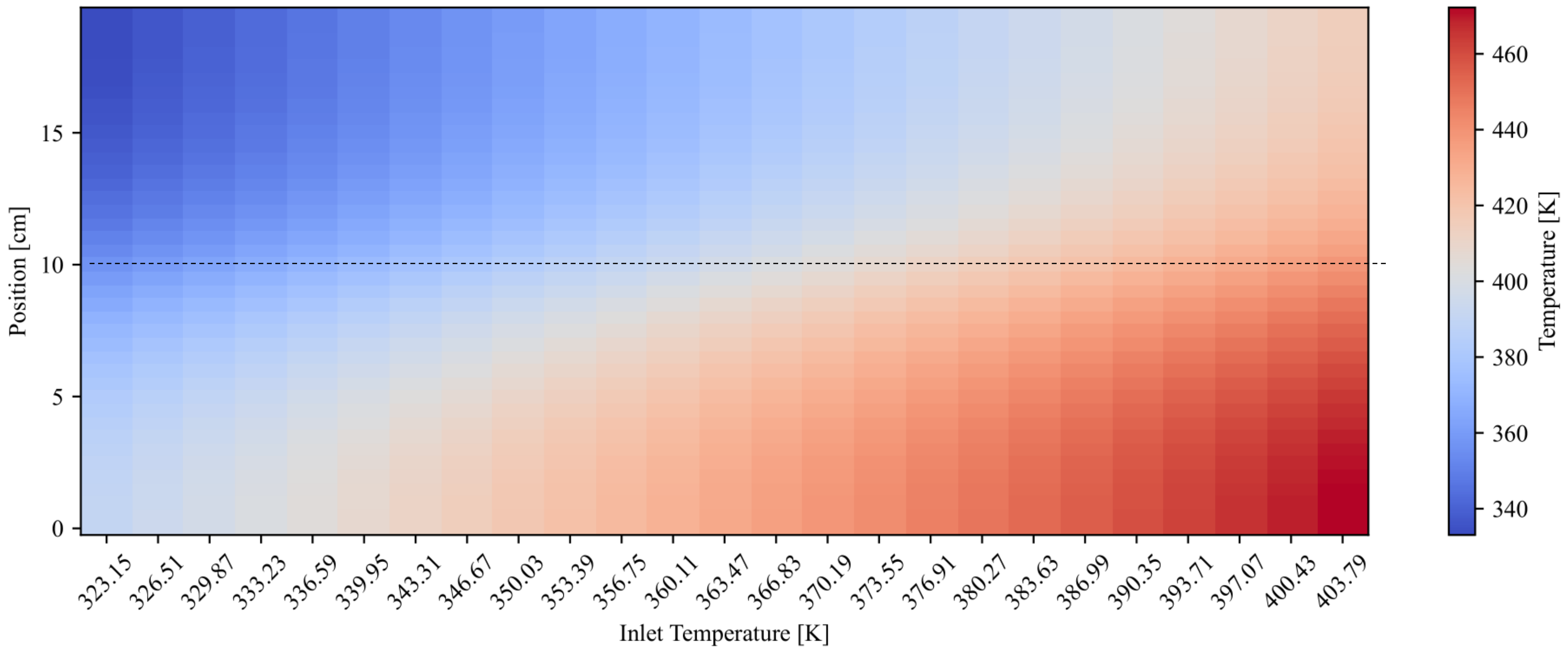
Mitigation of Temperature Gradients

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



Results

Mitigation of Temperature Gradients

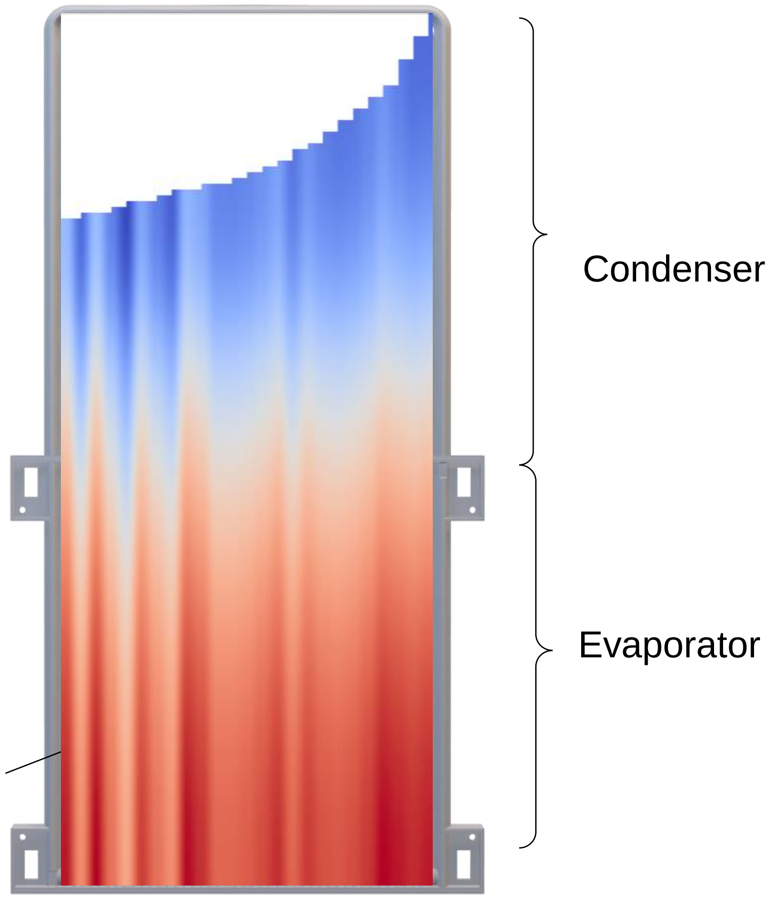


Results

Metigation of Temperature Gradients

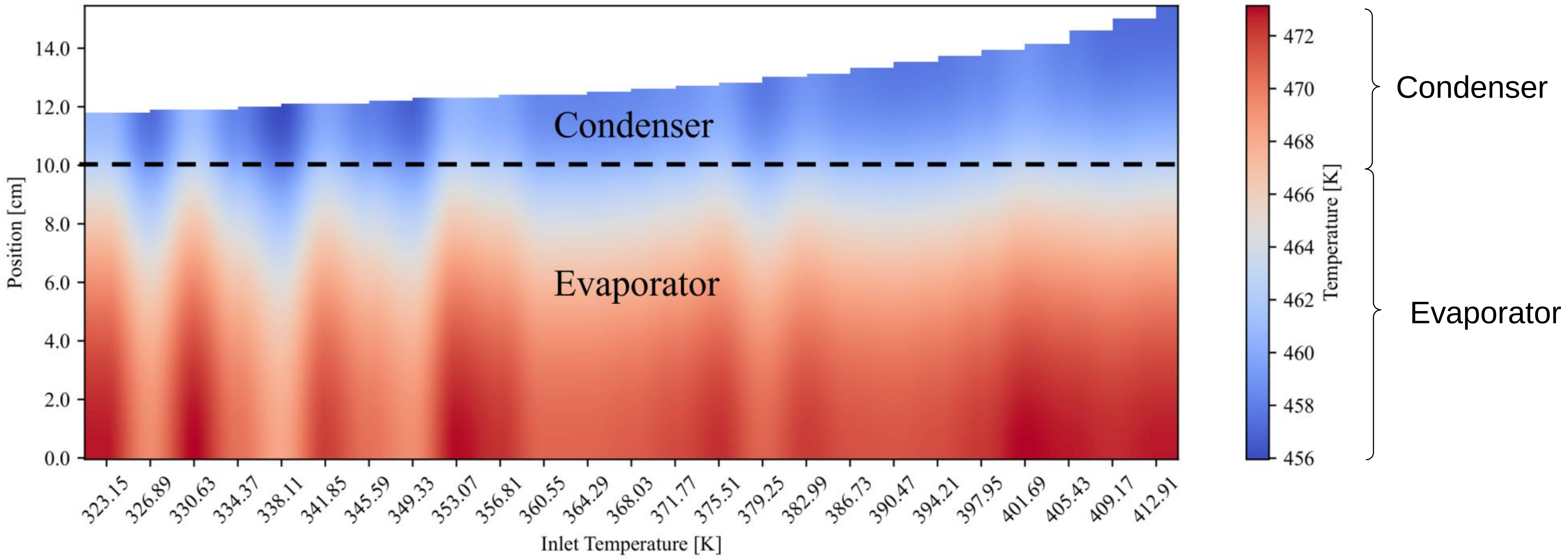
- **Vary condenser lengths**
  - **Each single strand must comply with maximum temperature**

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



Results

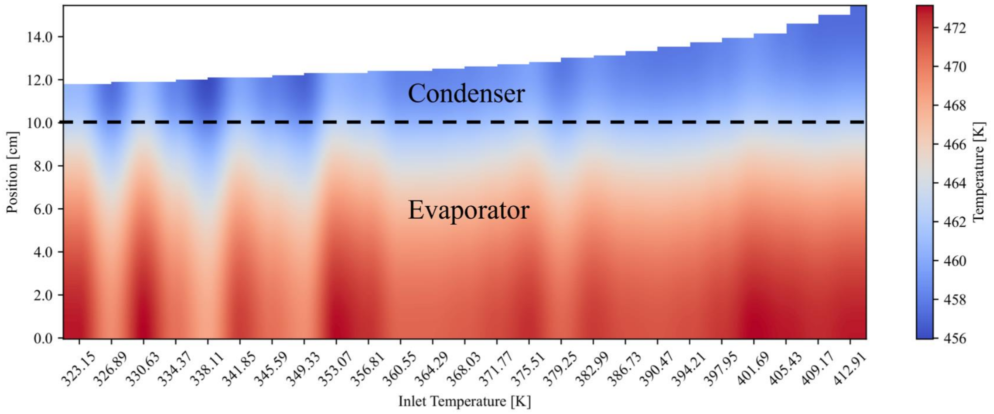
Metigation of Temperature Gradients



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

Heat Pipe Assisted Air Cooling for Fuel Cells in Aviation

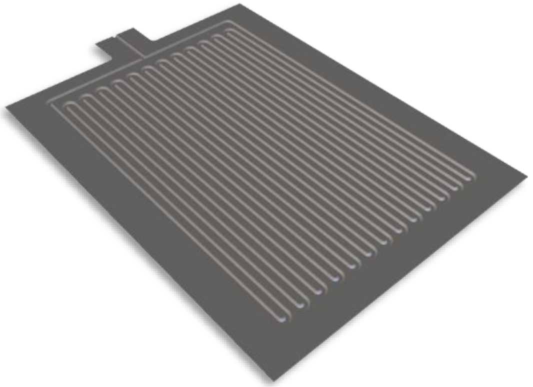
- Introduction
- Motivation & State of the Art
- Methodology
  - Development of a Thermal Model
  - Determine Feasibility for Fuel Cell TMS
- Results
  - Temperature Distribution
  - Design Modification
- **Conclusion & Outlook**



Conclusions

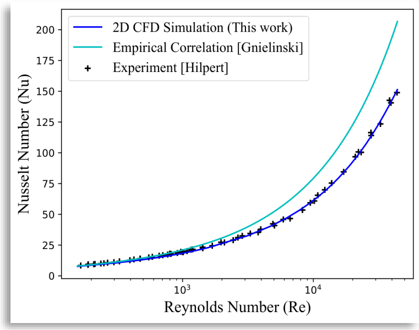
Heat Pipe assisted air cooling for fuel cells

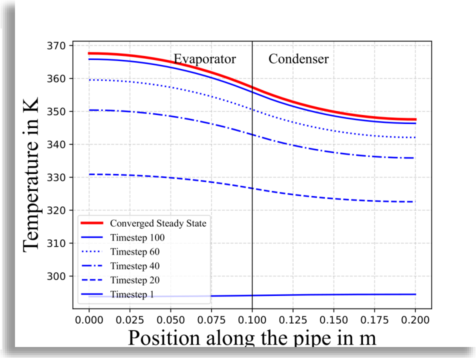
- A new concept to integrate PHP into fuel cells was introduced
- Potential advantages are increased simplicity and efficiency



1D Model

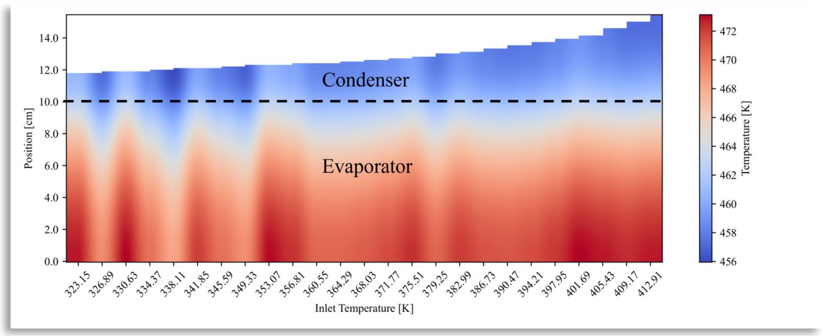
- 1D thermal model was implemented and validated
- Temperature distributions along a single pipe were calculated
- Thermal Conditions demonstrate theoretical feasibility for FC cooling





Design Adaptations

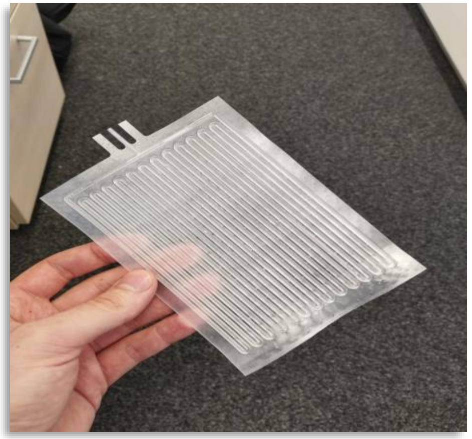
- Design adaptations for Mitigation of Temperature Gradiants introduced
- Improved temperature homogeneity was achieved



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

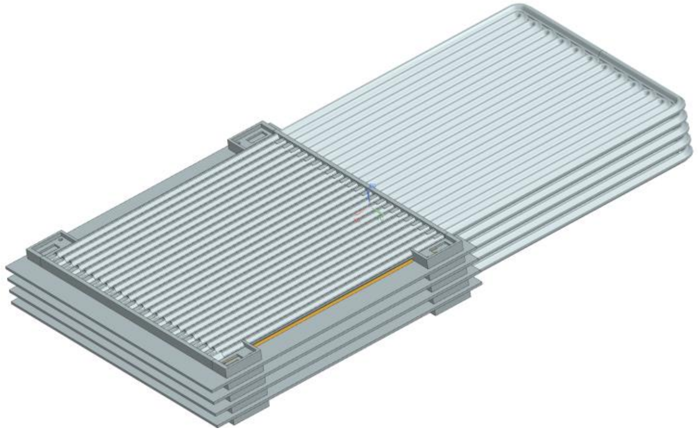


Testing

- 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] - Kühlkonzepte 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*

[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*

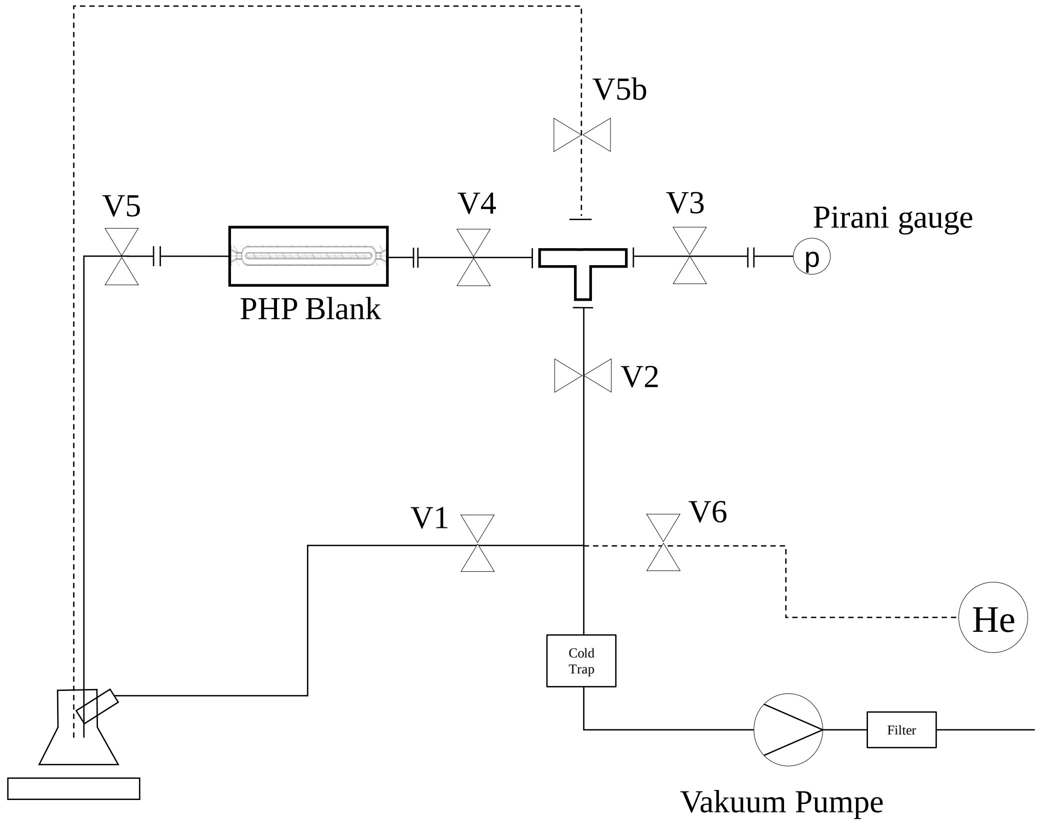
[Hilpert 1933] - Hilpert, R. Wärmeabgabe von geheizten Drähten und Rohren im Luftstrom*; DOI 10.1007/BF02719754*

Thank you for listening!

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

Mail: friedrich.franke@dlr.de

PHP Filling

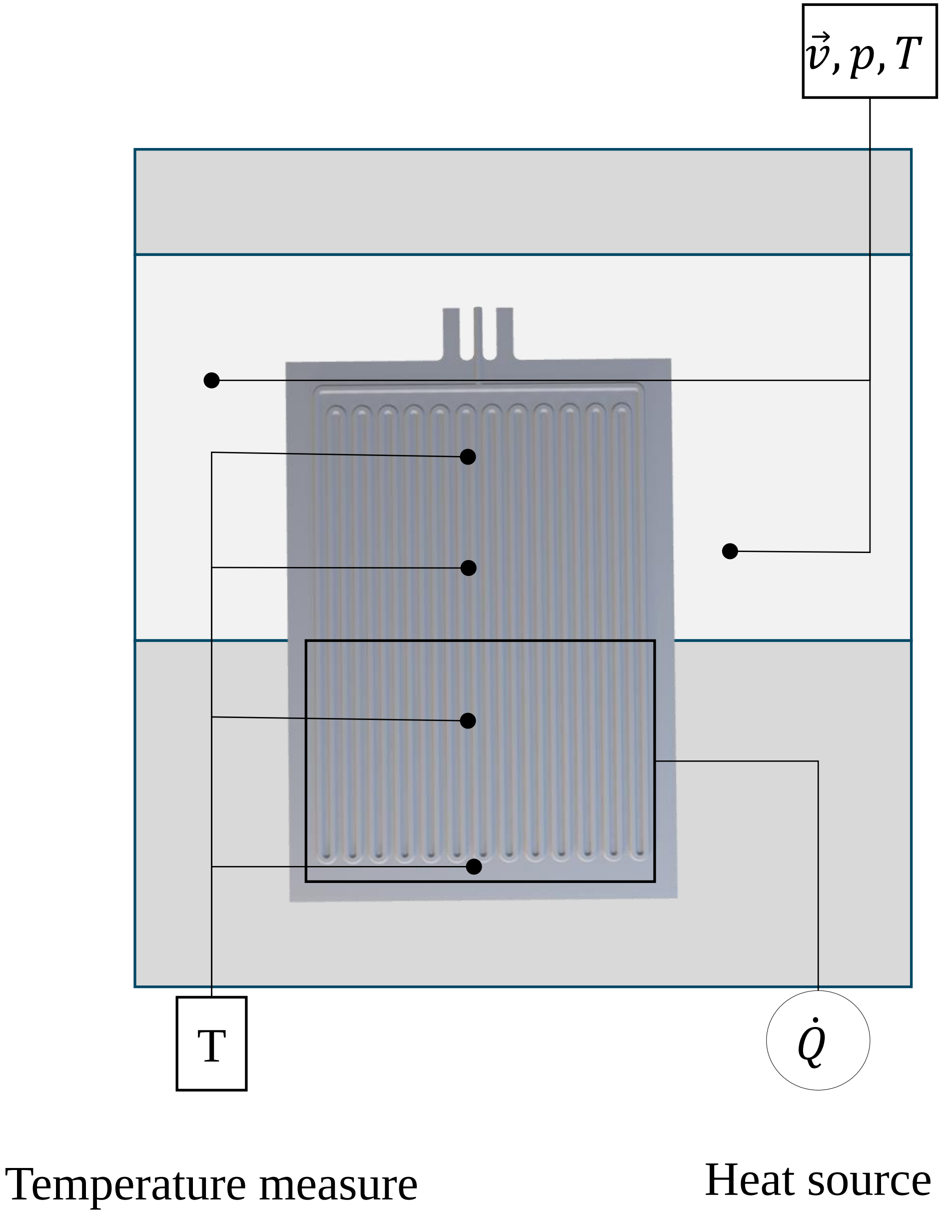

V5b
V5
V4
V3
Pirani gauge
p
PHP Blank
V2
V1
V6
He
Cold Trap
Filter
Vakuum Pumpe

Blank Demonstrator
Copper 3D Printing

Measuring Performance

(1) IPM & (2) – TMT MAD

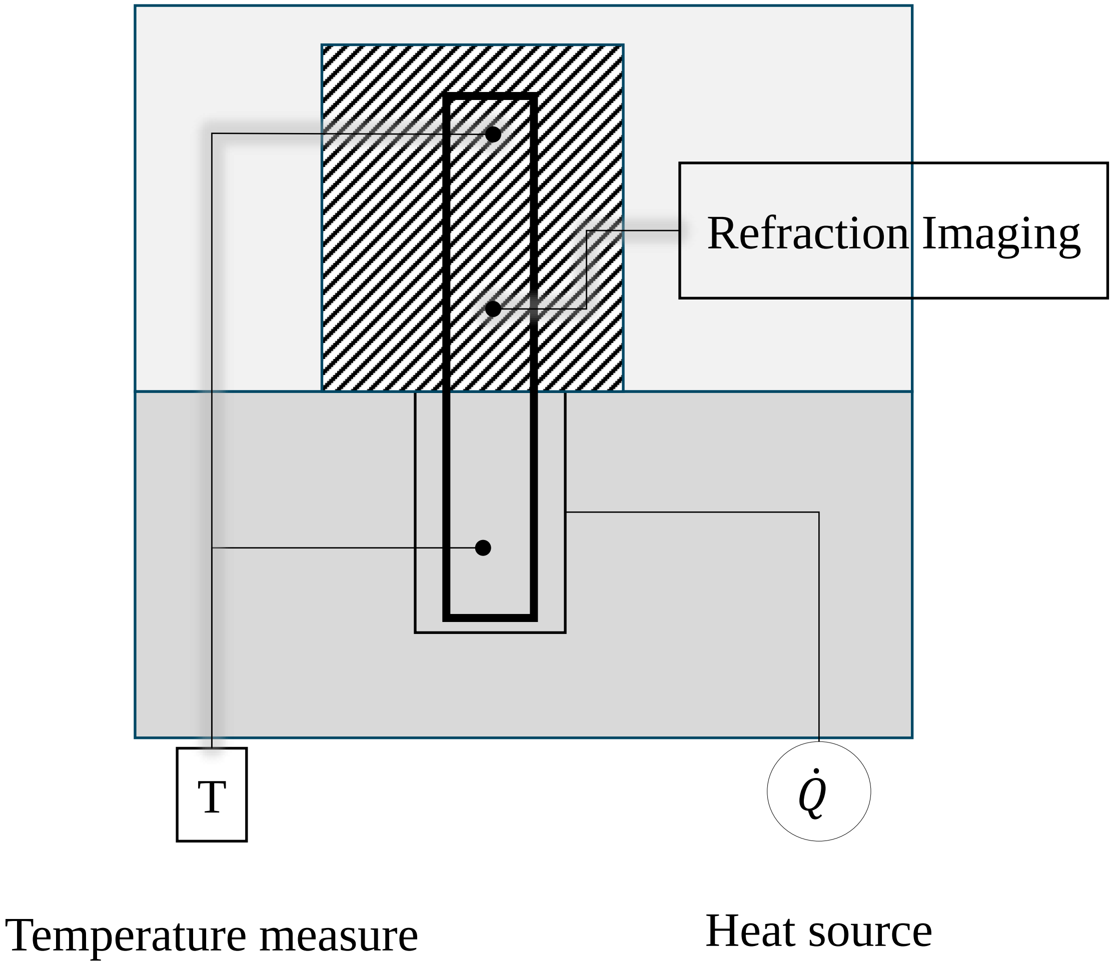
1. Temperature Sensors on outer wall
2. IR-camera (frontal view)
3. Testing Procedure: Stepwise increase of heating power at constant airspeed
4. Alter fan power
5. Install channel obstruction / Dummy stack



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

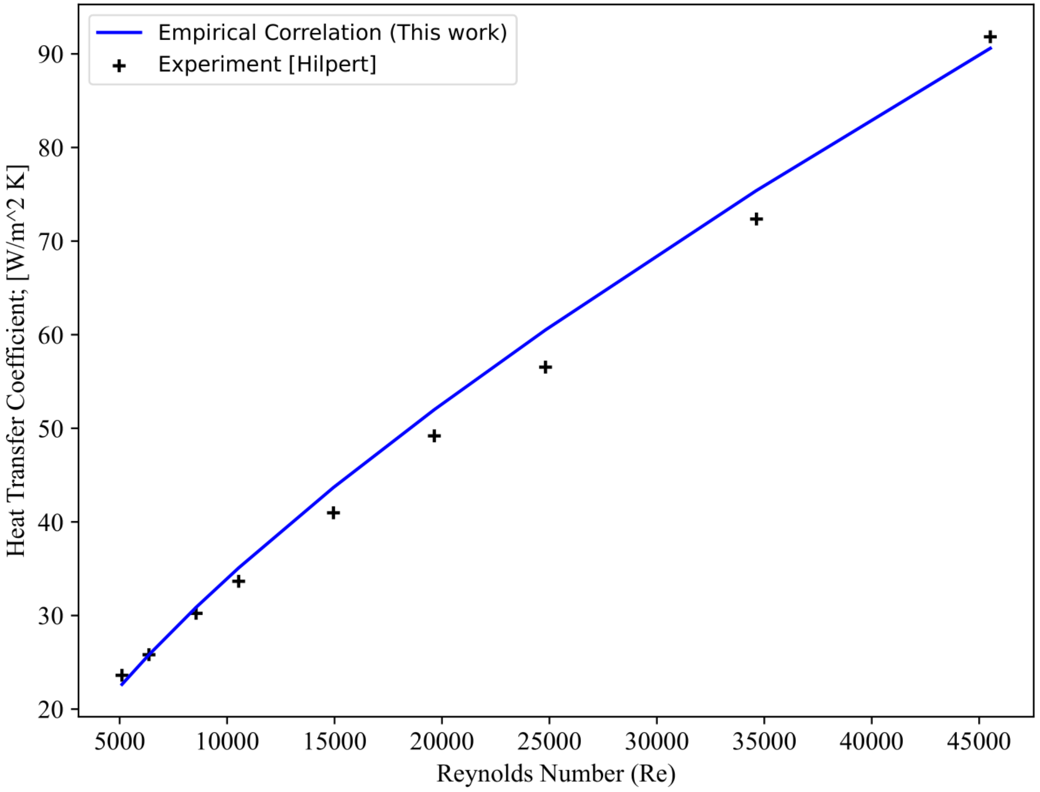


Analytical-empirical Modeling of Convection

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

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



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 cappilary 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**

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