EVAPORATION OF THE REFRIGERANT WATER

Previous and current research at Fraunhofer ISE


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Fraunhofer Institute for Solar Energy Systems ISE

25th IIR International Congress of Refrigeration

Montreal, August 24-30, 2019

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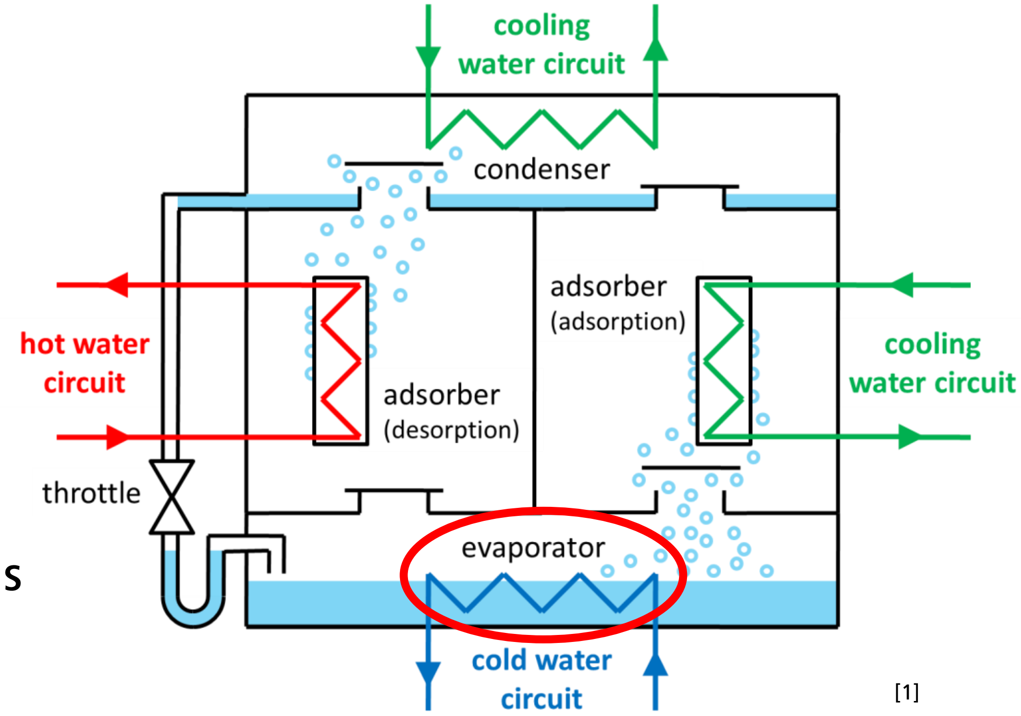
Background & Motivation
Evaporation of Water in Adsorption Heat Pumps / Chillers

- Typical conditions:
  - Refrigerant: water (pure refrigerant environment)
  - Evaporation at subatmospheric pressure:
    4-20°C / 8-25 mbar → unusual evaporation conditions
  - Low driving temperature differences

➢ Challenging conditions for effective evaporation

- Specific requirements for the evaporator:
  - High evaporation efficiency despite difficult conditions
  - Suitability for large vapor volumes
  - Vacuum tightness + corrosion stability
  - Compact & low-cost design



[1]

[1] Hoffmann, A. (2008). Bestimmung der Verdampfungseigenschaften verschiedener Verdampferstrukturen im Niederdruckbereich, Technische Fachhochschule Berlin.

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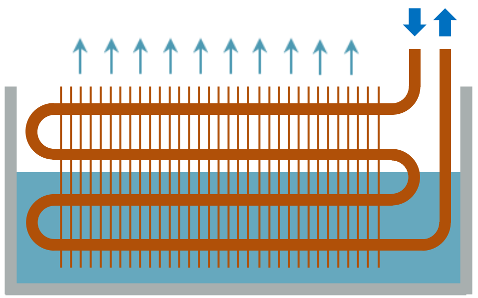
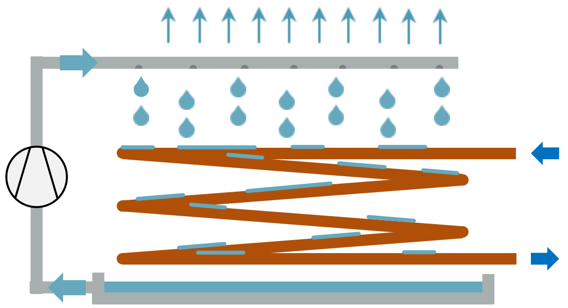
Operational Modes
State of the Art

Pool boiling	Evaporation from thin films
Convective boiling	Falling film operation
→ *low heat transfer*	→ *auxiliary energy required*





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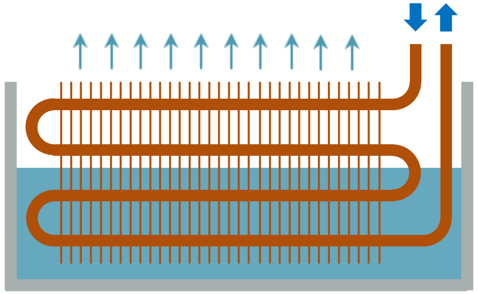
Operational Modes
State of the Art

Pool boiling

Convective boiling

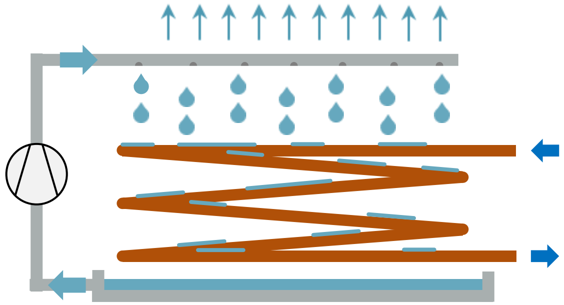
→ low heat transfer



Evaporation from thin films

Falling film operation

→ auxiliary energy required



How can evaporator performance be improved?

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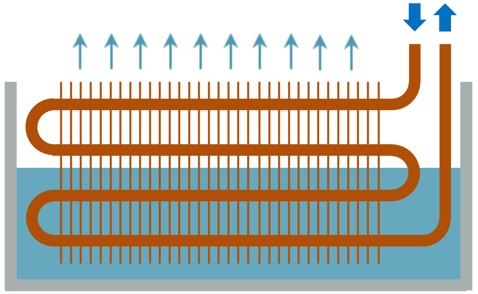
Operational Modes

State of the Art

Pool boiling

Convective boiling

→ *low heat transfer*

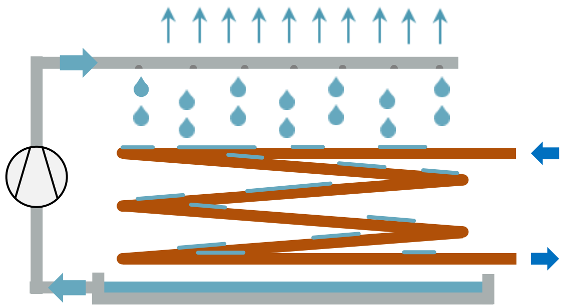


Facilitate bubble formation!

Evaporation from thin films

Falling film operation

→ *auxiliary energy required*



Create thin films with capillary structures!

How can evaporator performance be improved?

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Operational Modes
Innovative approaches

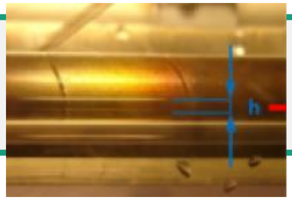
Pool boiling

Evaporation from thin films

Convective boiling

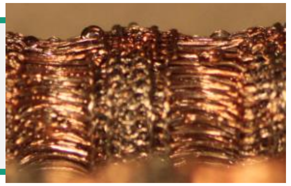
Falling film operation

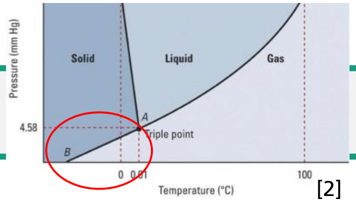
Facilitated nucleate boiling with porous structures



Steady-state partially flooded evaporation with capillary structures

Cyclic capillary-assisted evaporation





[2]

→ special case: evaporation below 0°C

[2] https://chemdemos.uoregon.edu/sites/chemdemos1.uoregon.edu/files/PhaseDiagramWater.jpg

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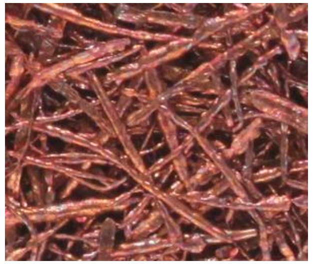
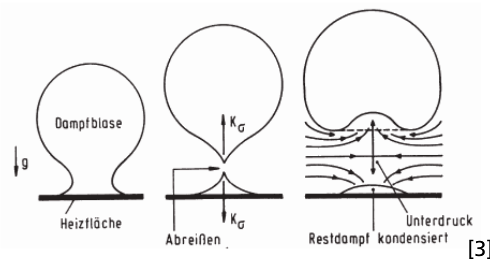
Facilitated nucleate boiling with porous structures
Approach

- Shift the regime of nucleate boiling to lower wall superheats
- Utilization of structured / porous surfaces
  - facilitated bubble formation due to more available nucleation sites
  - higher heat transfer coefficient





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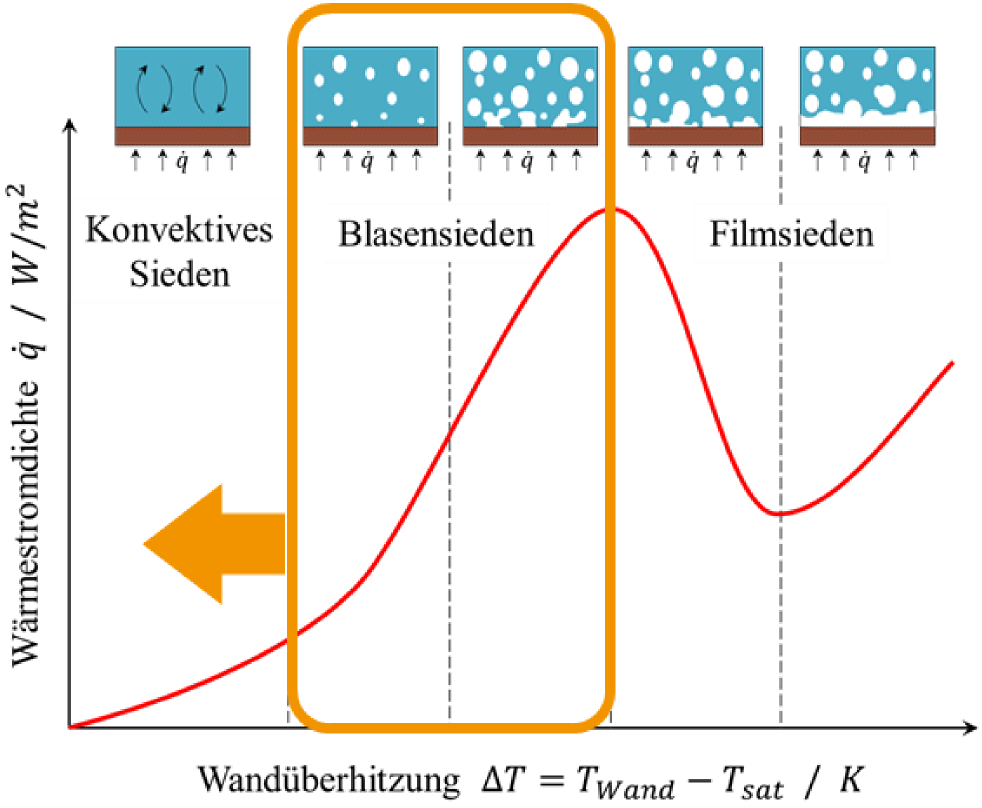

[3] H. D. Baehr and K. Stephan, Wärme- und Stoffübertragung, 6th ed. Berlin; Heidelberg: Springer, 2008.

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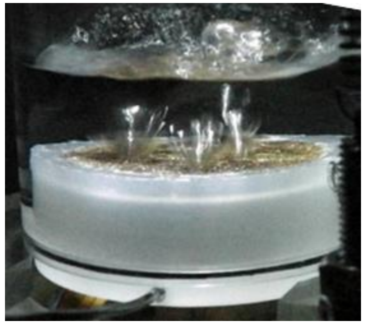
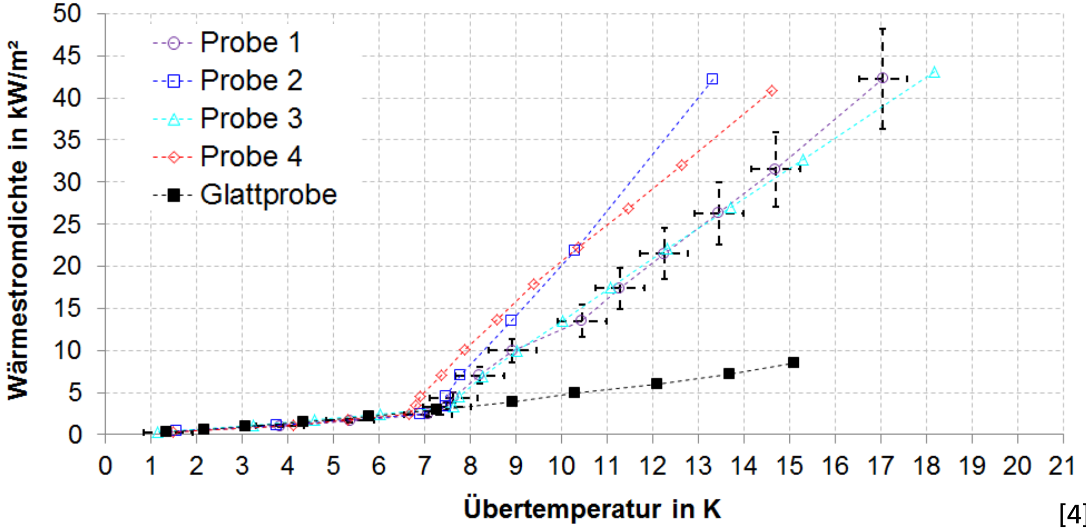
Facilitated nucleate boiling with porous structures

Example: Dissertation Kai Witte/ SorCool-Projekt (FKZ 0327423B)

"Experimental Investigations on Boiling in Metal Fiber Structures at Low Pressures"

- Samples: Sintered copper fiber structures
- Determination of boiling curves and required wall superheats (ΔT) for nucleate boiling





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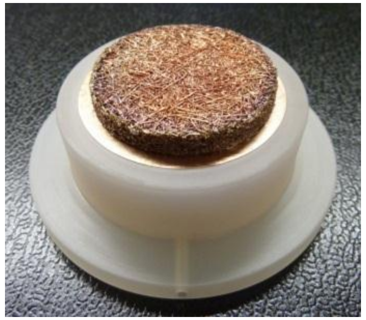

[5]

[4]

➢ Required superheat can be substantially decreased, but remains relatively high

[4] Witte, Kai Thomas, 2016, Experimentelle Untersuchungen Zum Sieden in Metallfaserstrukturen Im Bereich Niederer Drücke. Dissertation, Technische Universität Darmstadt. http://tubiblio.ulb.tu-darmstadt.de/80254/.

[5] Abschlussbericht Projekt SorCool, Fraunhofer ISE, Freiburg, 2012

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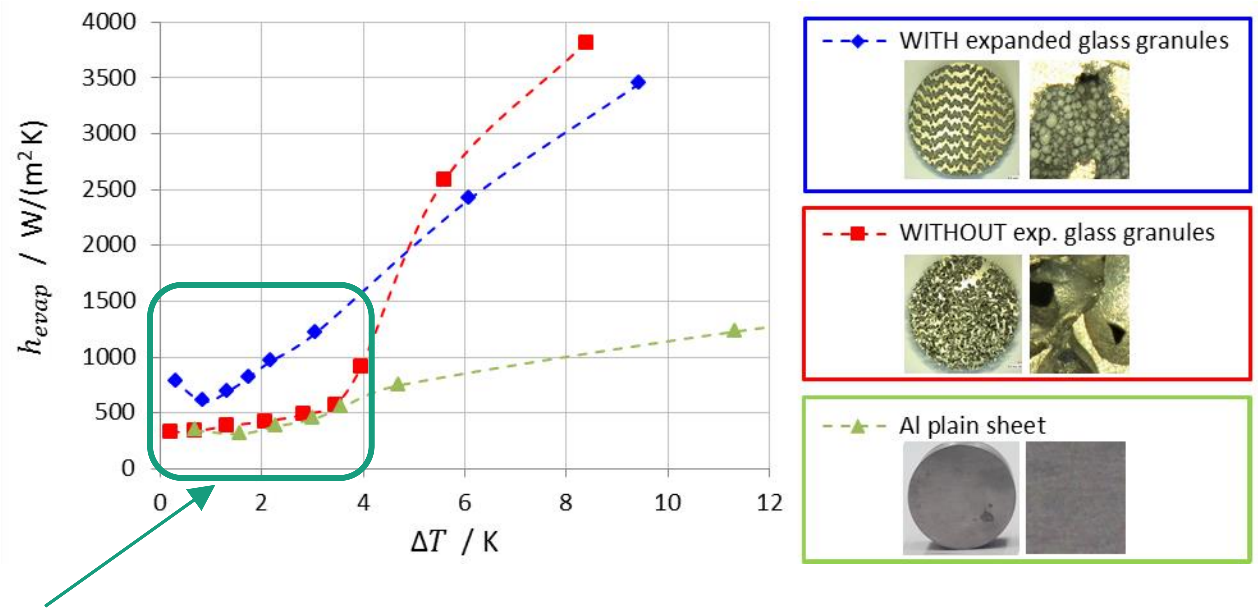
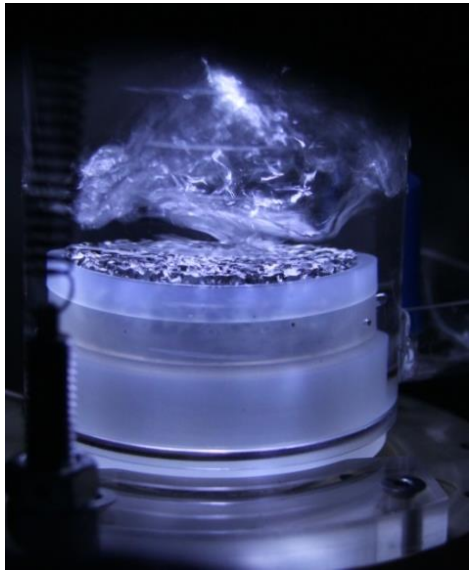
Facilitated nucleate boiling with porous structures

Example: Project "HArVest" (2015-2018)

- Composite material: Aluminum foam with surface-embedded expanded glass granules
- Idea: expanded glass granules act as nucleation sites





- Low wall superheat: Sample with granules performs better
- Pore morphology probably plays a role as well

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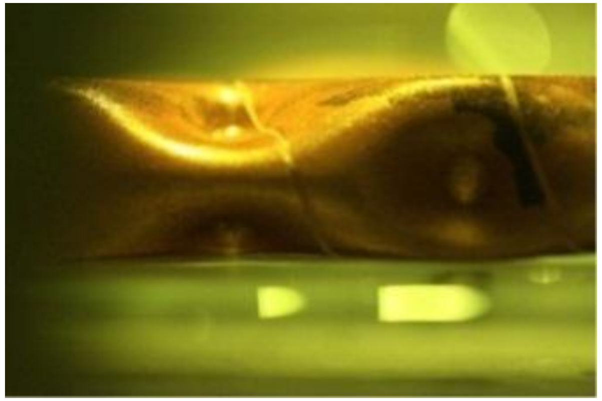
Steady-state partially flooded evaporation with capillary structures

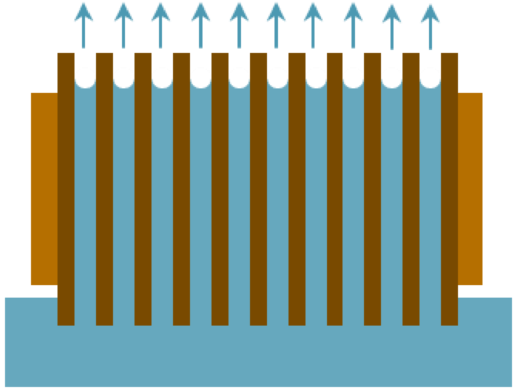
Approach

- Partially-flooded capillary structures
  (e.g. finned tubes / micro-/macro-structured tubes)
  - Formation of thin refrigerant films / 3-phase contact lines
  - High heat transfer, efficient evaporation from menisci
  - Refrigerant transport without auxiliary energy demand



[5]

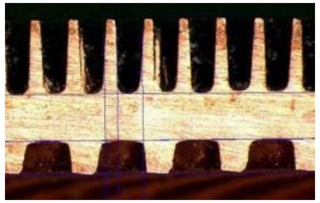
- Drawback: strong sensitivity to refrigerant filling level
  - Precise adjustment of tubes / filling level required



[5] Abschlussbericht Projekt SorCool, Fraunhofer ISE, Freiburg, 2012

Steady-state partially flooded evaporation with capillary structures

Example: SorCool-Projekt (FKZ 0327423B)



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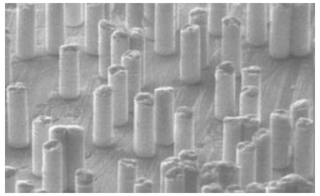
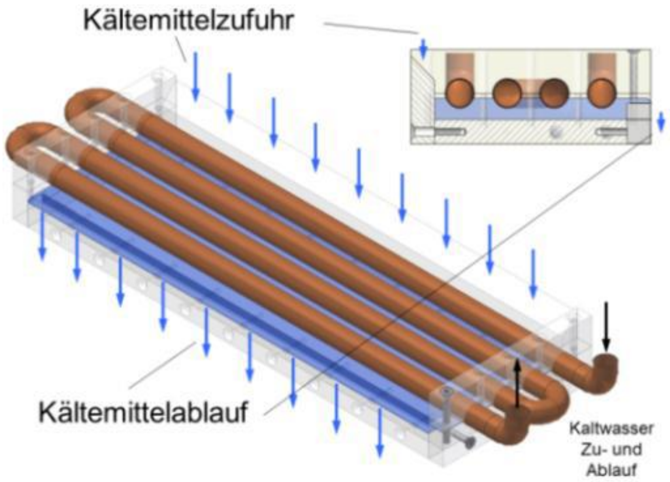


[3]

Steady-state evaporation on partially-flooded structured tubes

- Impact of different internal & external structures (fins, micro pins, etc.)
- Impact of refrigerant filling level
- Assessment of heat transfer coefficients in dependence of process parameters
  → derivation of design guidelines / correlations



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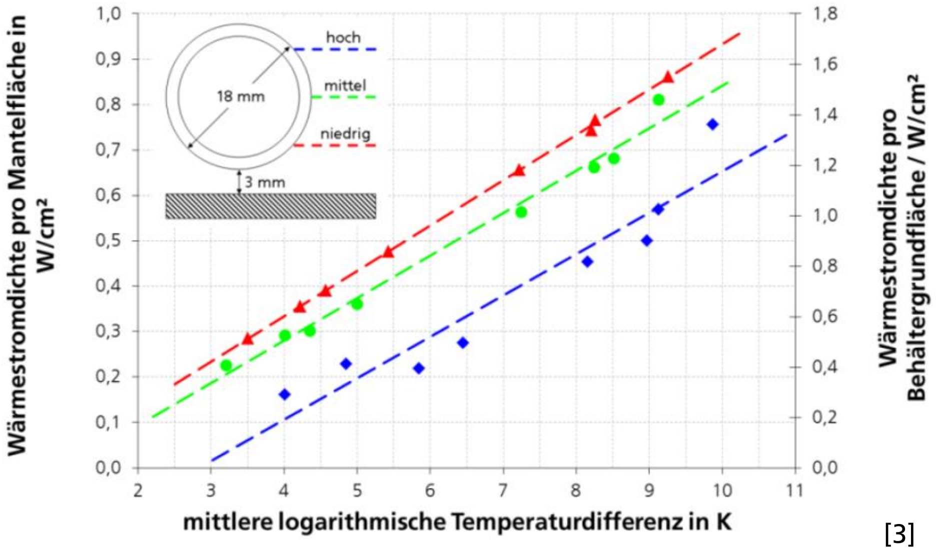
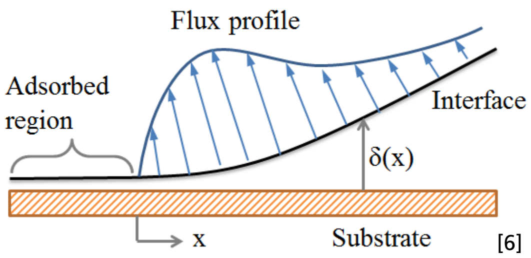


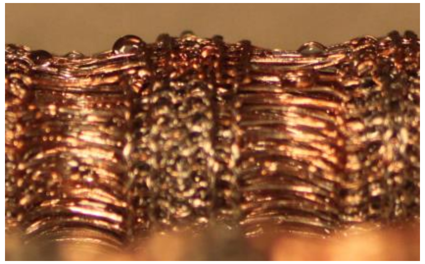
[3]

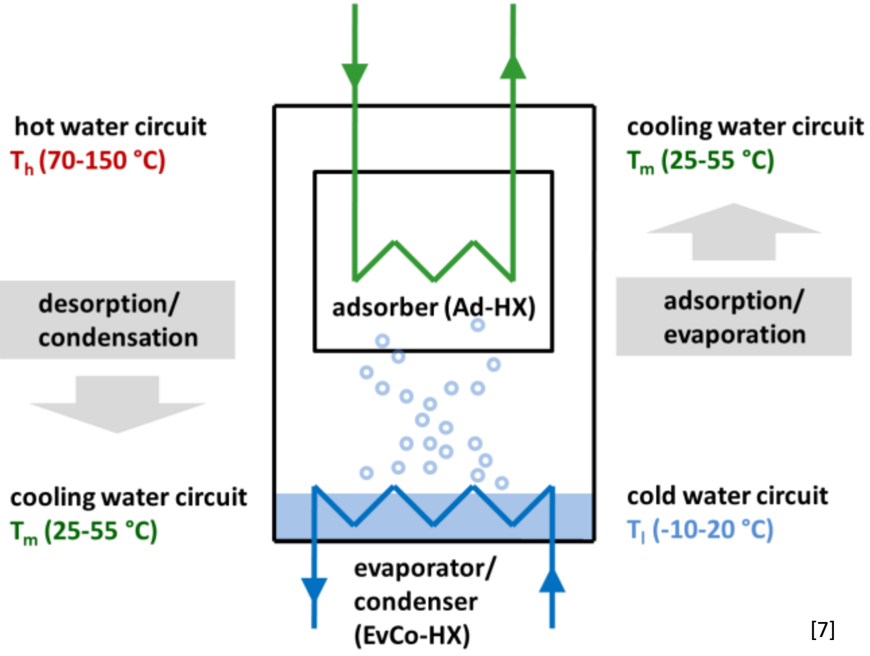
[5] Abschlussbericht Projekt SorCool, Fraunhofer ISE, Freiburg, 2012

Cyclic capillary-assisted evaporation
Approach

- Formation of thin refrigerant films (microzones) on/in capillary structures
  - High evaporation heat transfer achievable
- Cyclic condensation and evaporation on one heat exchanger
  - Refrigerant supply by condensation → no auxiliary energy required
- Cyclic operation entails:
  - Dynamic evaporation process
  - One-chamber sorption module → compact design
  - Thermal masses must be minimized to avoid losses
  - Limited refrigerant turnover per half-cycle



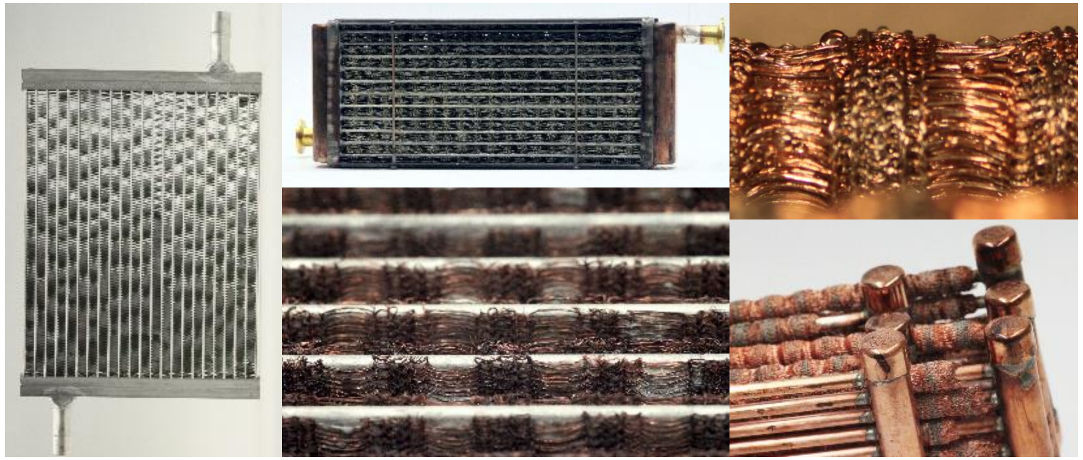




[6] M. S. Hanchak et al. "Thin Film Evaporation Model With Retarded van der Waals Interaction," 2013, p. V08CT09A044.
[7] Schnabel, L. et al., Springer 2017, ISBN 978-3-319-71639-8.

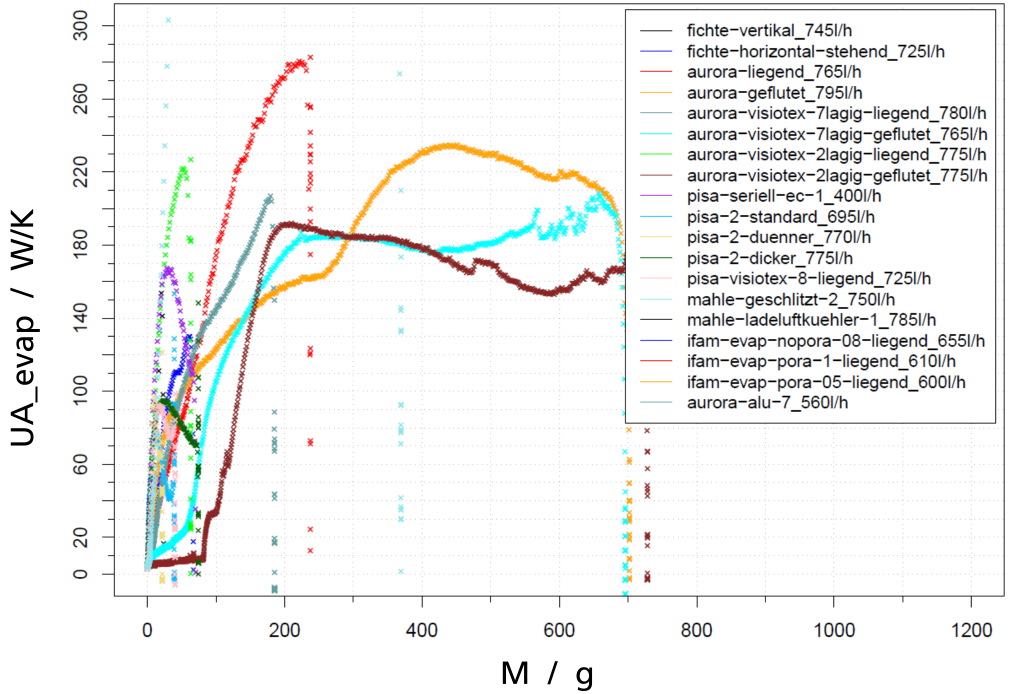
Cyclic capillary-assisted evaporation

Example: Project "HArVest"



Cyclic non-stationary evaporation measurements on different evaporator designs

- Innovative evaporator designs with porous structures
- Development of manufacturing technology
- Measurement and assessment of evaporation performance and dynamics



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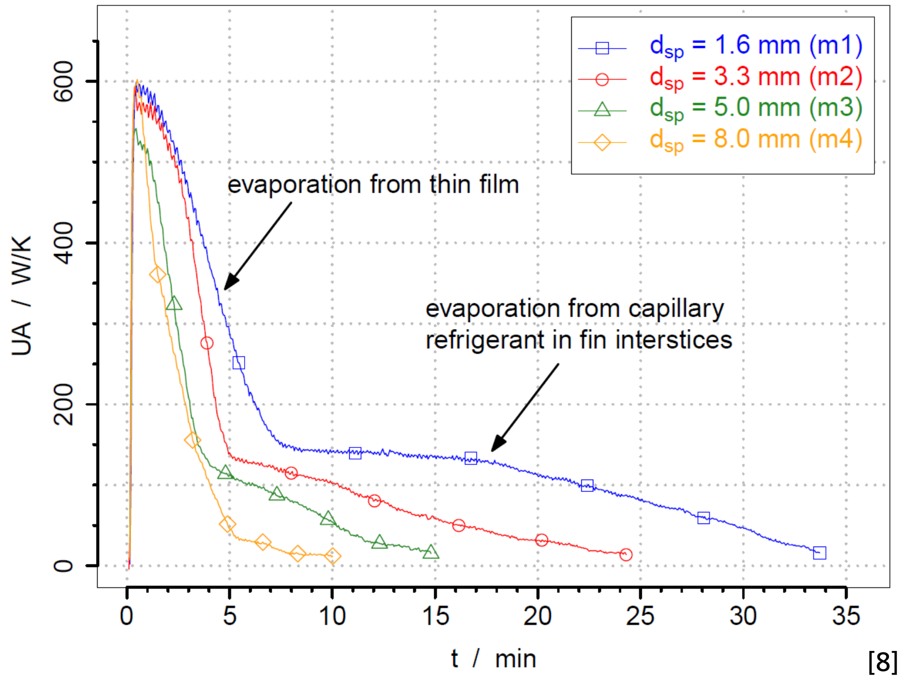
Cyclic capillary-assisted evaporation

Example: Project "ADOSO" (FKZ 03ET1127 B)

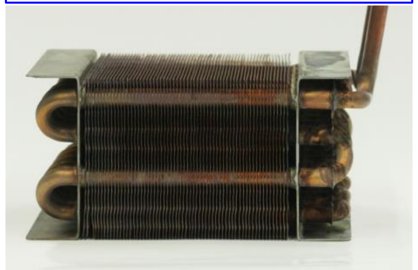
Analysis of geometry impacts on dynamic thin film evaporation

- Samples: Cu tube-fin heat exchangers
- Variation of fin spacing, fin thickness, tube diameter
- Refrigerant storage on fin surfaces and in interstices
- Analysis of (de-)wetting and evaporation dynamics

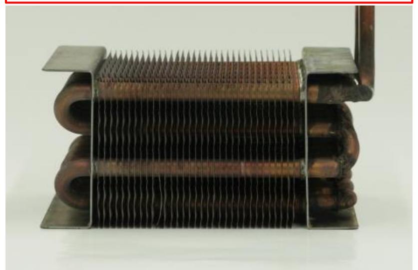


[8]

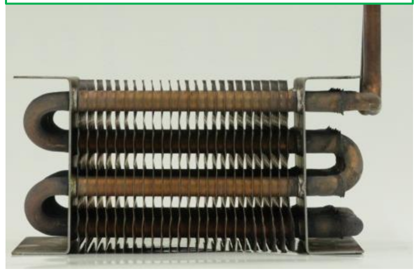
1.6 mm fin distance



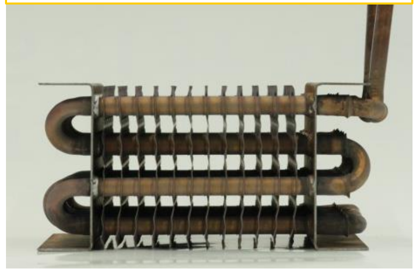
3.3 mm fin distance



5.0 mm fin distance



8.0 mm fin distance



[8] R. Volmer, et al., Evaporator development for adsorption heat transformation devices – Influencing factors on non-stationary evaporation with tube-fin heat exchangers at sub-atmospheric pressure, Renewable Energy (2016), http://dx.doi.org/10.1016/j.renene.2016.08.030

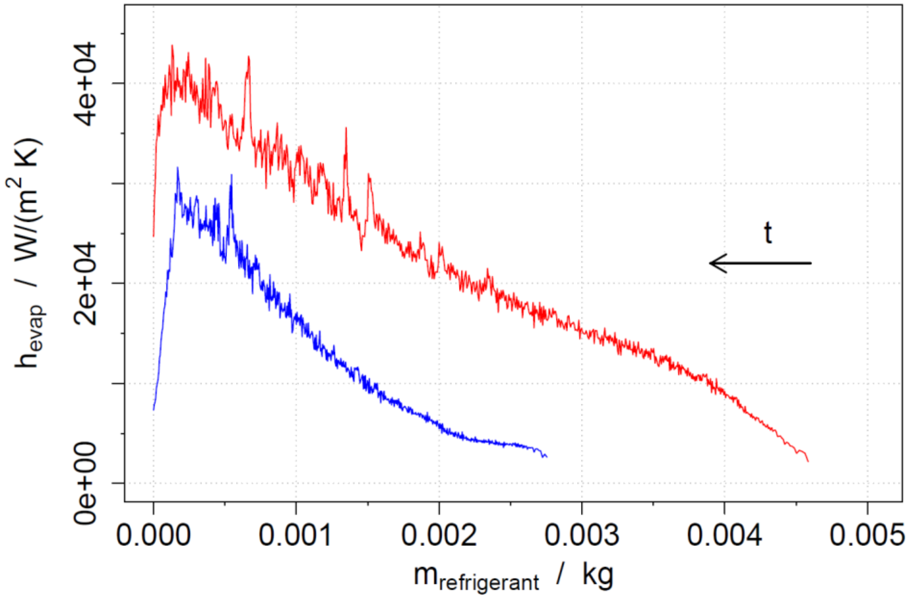
Cyclic capillary-assisted evaporation

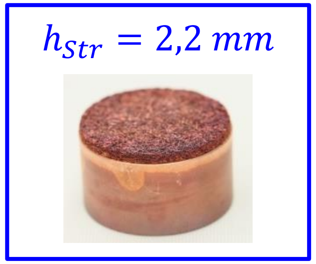
Example: Project “ADOSO” (FKZ 03ET1127 B)

Dynamic capillary-assisted evaporation from porous Cu fiber structures

- Samples: sintered Cu fiber structures, soldered on carrier
- Variation of structure height: 2.2 mm vs. 5.0 mm

- Heat transfer coefficient U_{evap} rises with reducing refrigerant charge
- Higher structure achieves higher U_{evap} and refrigerant storage capacity





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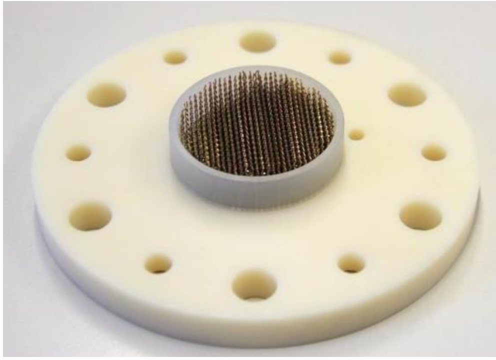
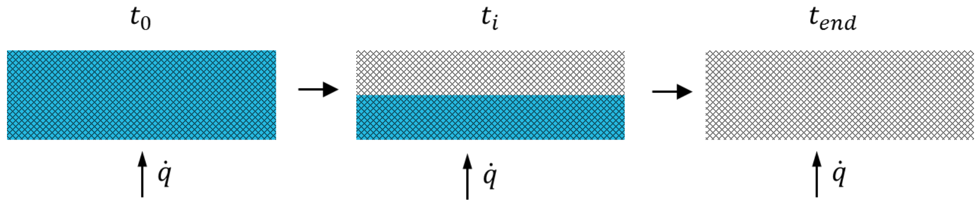
Cyclic capillary-assisted evaporation

Example: Dissertation Rahel Volmer

Characterization of dynamic evaporation from copper wire mesh structures

- Samples: parallel Cu wire mesh strips, soldered on carrier
- Analysis of …
  - geometry impacts: variation of pore size, porosity, structure height, wire orientation
  - process impacts: system pressure, applied heat flux
  - impact of surface properties
  - interaction of wetting dynamics and evaporation dynamics
- Comparison with modeling results, deduction of design guidelines





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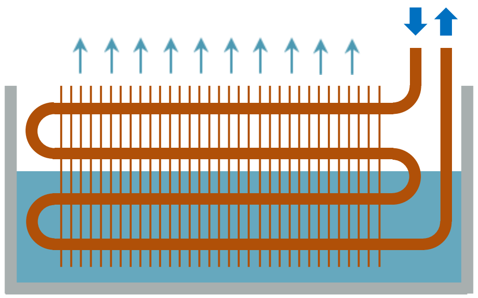
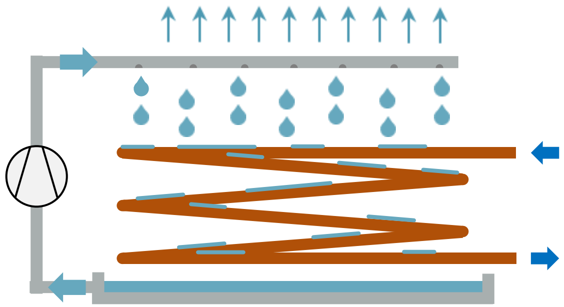
Operational Modes

State of the Art - conclusion

Pool boiling	Evaporation from thin films
HTC in a range of 500 – 3000 W/m²K possible	HTC in a range of 100 – 10000 W/m²K possible



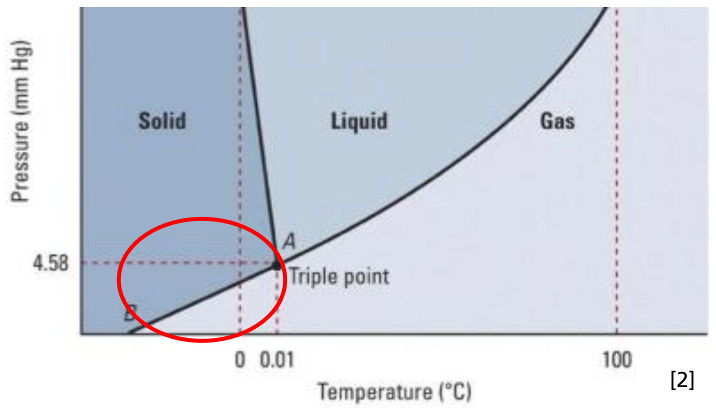


different technical concepts available, but modified heat exchangers are necessary

by knowing the relevant effects … make it simple again …

What's next: evaporation below 0°C
research network of "SubSie" projects

- Evaporation usually limited to > 0°C due to risk of freezing
- Perspectives for evaporation below 0°C for aBsorption / aDsorption heat pumps / chillers:
  - heat pumps: → utilization of ambient air as low T heat source
  - chillers: → significant extension of the scope of application
- Challenge: development of evaporator & module concepts which…
  - tolerate temperatures below 0°C (→ freezing / lower freezing point / …)
  - supply sufficient evaporation power



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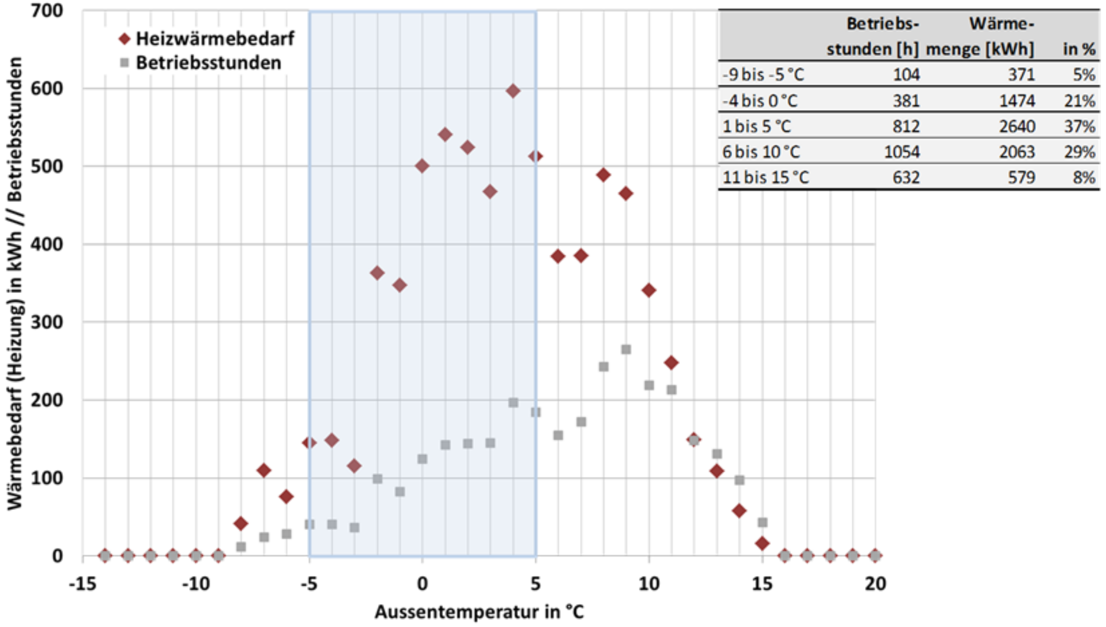

	Betriebs-stunden [h]	Wärme-menge [kWh]	in %
-9 bis -5 °C	104	371	5%
-4 bis 0 °C	381	1474	21%
1 bis 5 °C	812	2640	37%
6 bis 10 °C	1054	2063	29%
11 bis 15 °C	632	579	8%

[2] https://chemdemos.uoregon.edu/sites/chemdemos1.uoregon.edu/files/PhaseDiagramWater.jpg

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What’s next: evaporation below 0°C
research network of “SubSie” projects

- consortium of 12 academic and industrial partners, working with water as refrigerant
- Five technology projects, addressing different technical solutions to make the use of water around the freezing point feasible
- Technology projects are linked with a science and market project (Fraunhofer ISE/ TU Berlin) in order to ensure scientific quality and coordination the market activities
- Three projects started in 2019, the open three will start latest until 05/20
- Total project volume: 7,5 Mio. €/ 5,5 Mio. € funding

Wasser als Kältemittel – Nutzbar für die Zukunft!

Supported by:

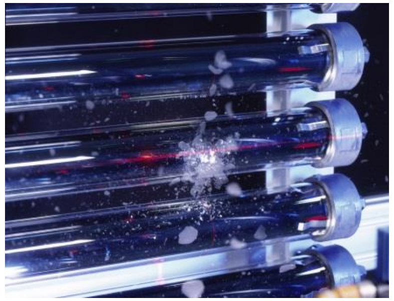
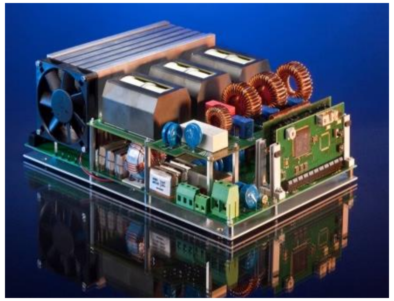
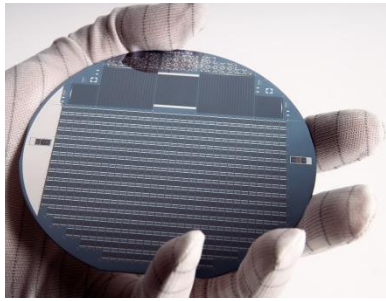
Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

grant no. 03EN2012A

Thank you for your Attention!

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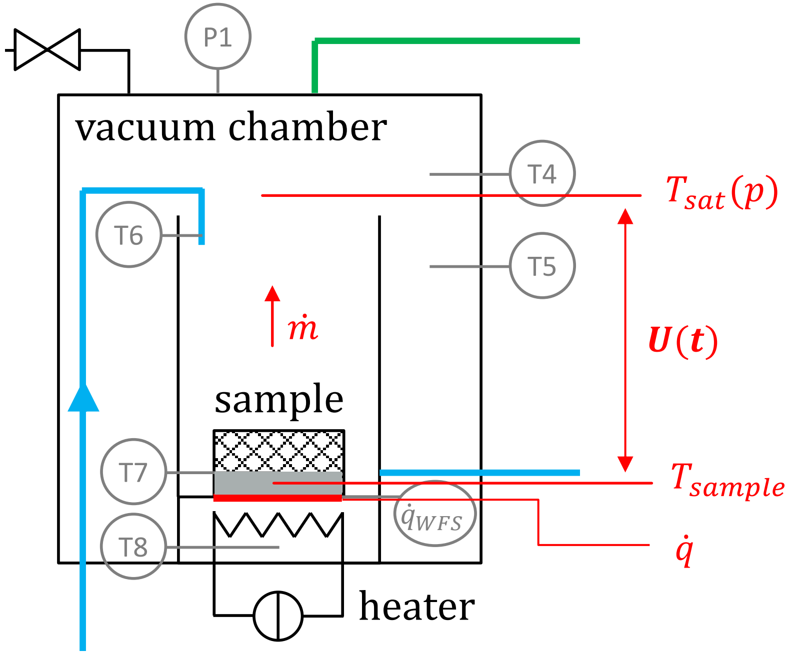
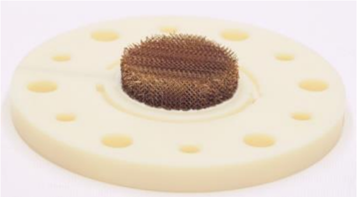
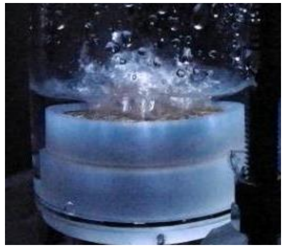
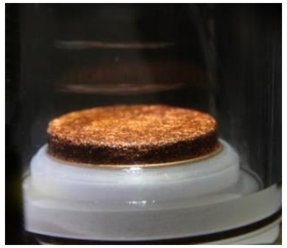
Experimental Setups

Setup for evaporation on structure samples









[5]

- Analysis of evaporation characteristics of small structure samples (Ø 40 mm)
- Operational modes:
  - Steady-state pool boiling
  - Dynamic pool boiling (flooded / partially flooded)
  - Dynamic capillary-assisted evaporation
- Evaluation quantities:
  - Steady-state: boiling curve $\dot{q} = f(\Delta T)$
  - Dynamic: heat transfer coeff.

$$U(t) = \frac{\dot{q}(t)}{T_{sample}(t) - T_{sat}(p,t)}$$

[5] Abschlussbericht Projekt SorCool, Fraunhofer ISE, Freiburg, 2012

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Experimental Setups

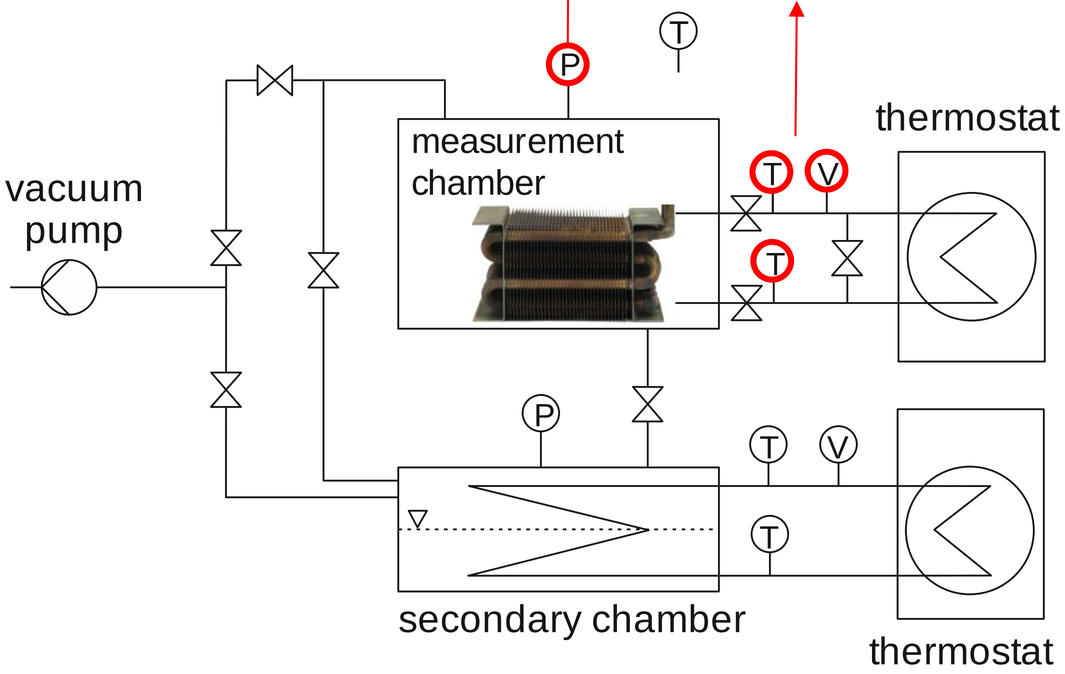
Setup for evaporation on heat exchangers

- Measurement of evaporation characteristics of heat exchangers
- Evaporation and condensation, steady-state and dynamic
- Various heat exchanger designs installable
- Operational modes:
  - (partially) flooded
  - falling film
  - cyclic capillary assisted / thin film
- Evaluation quantity:
  - "heat transfer capability" UA
    → independent of driving force

$$UA = \frac{\dot{Q}_{evap}}{\Delta T_{lm}}$$

with $\Delta T_{lm} = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in} - T_{sat}}{T_{out} - T_{sat}}\right)}$

$$\dot{Q}_{fluid} = \rho_{Fluid} \cdot \dot{V} \cdot c_p \cdot (T_{out} - T_{in})$$



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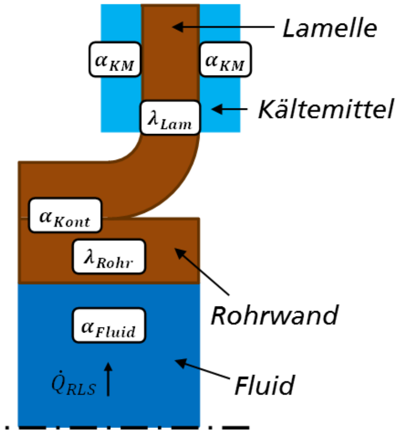
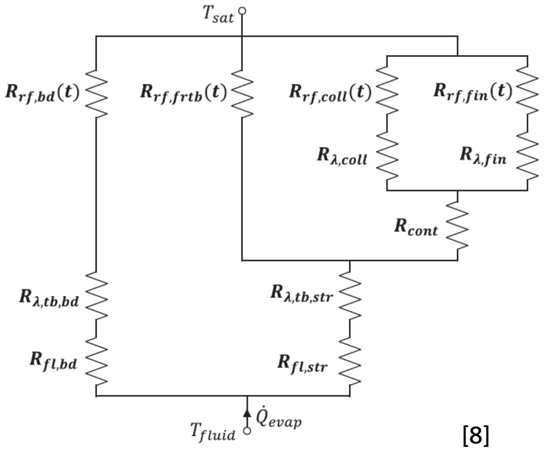
Modeling

Model for dynamic evaporation from tube-fin heat exchangers

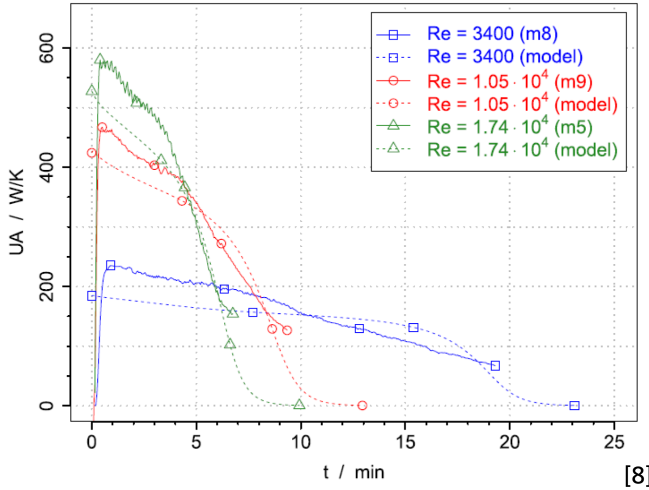
- Thermal resistance network model (node model)
- Input parameters: heat exchanger geometry (e.g. fin spacing, fin thickness), fluid temperature, system pressure, driving T difference

[8]





[8]



[8]

- ➢ Evaporation dynamics are reproduced qualitatively correct
- ➢ Quantitative model accuracy is improvable
- ➢ Resistance analysis allows identification of limiting factors

[8] R. Volmer, et al., Evaporator development for adsorption heat transformation devices – Influencing factors on non-stationary evaporation with tube-fin heat exchangers at sub-atmospheric pressure, Renewable Energy (2016), http://dx.doi.org/10.1016/j.renene.2016.08.030

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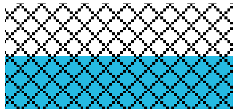
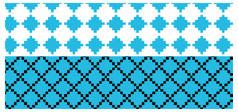
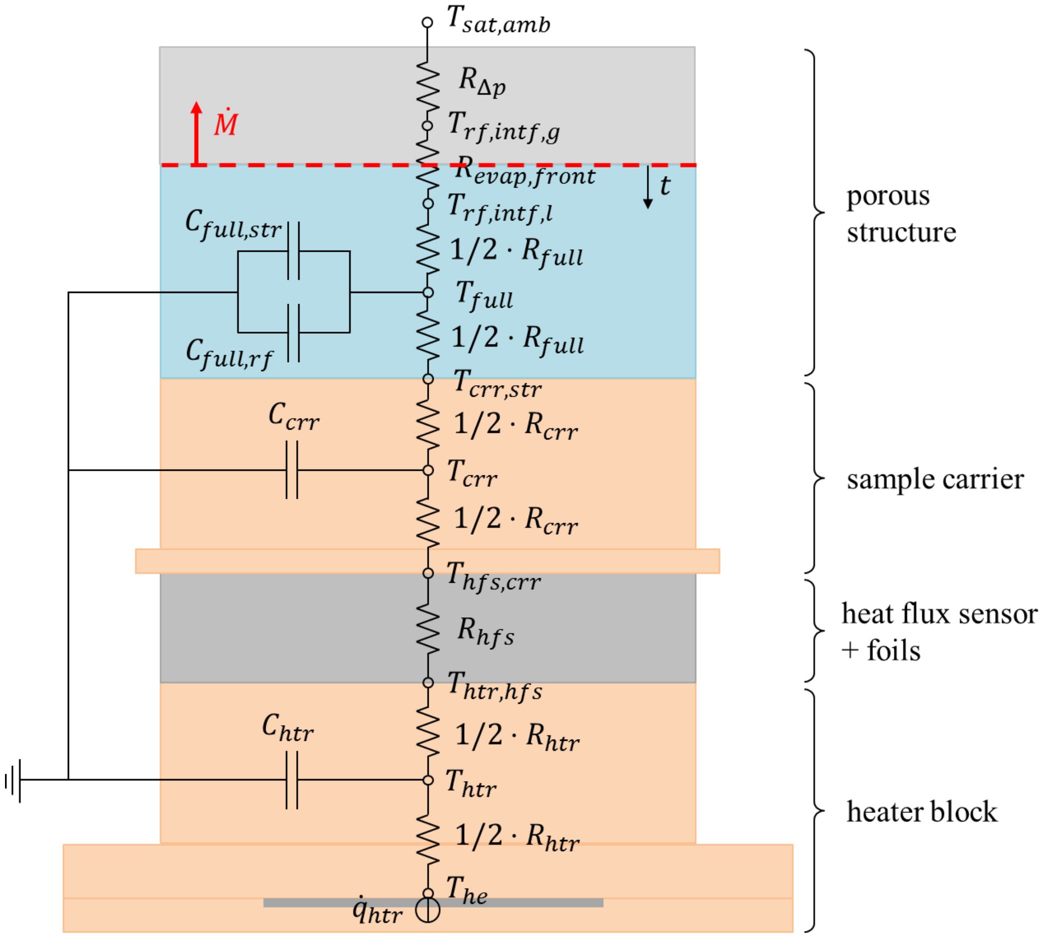
Modeling

Model for dynamic evaporation from porous structures

- Thermal RC network model (node model)
- Implementation in „R“
- Description of structure morphology by effective quantities (pore diameter, porosity, …)
- Different model approaches for (de-)wetting dynamics
  - Downward evaporation front →
  
  - Evaporation front + evap. from distributed refrigerant →
  
  - …
- ➢ Work in progress…



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