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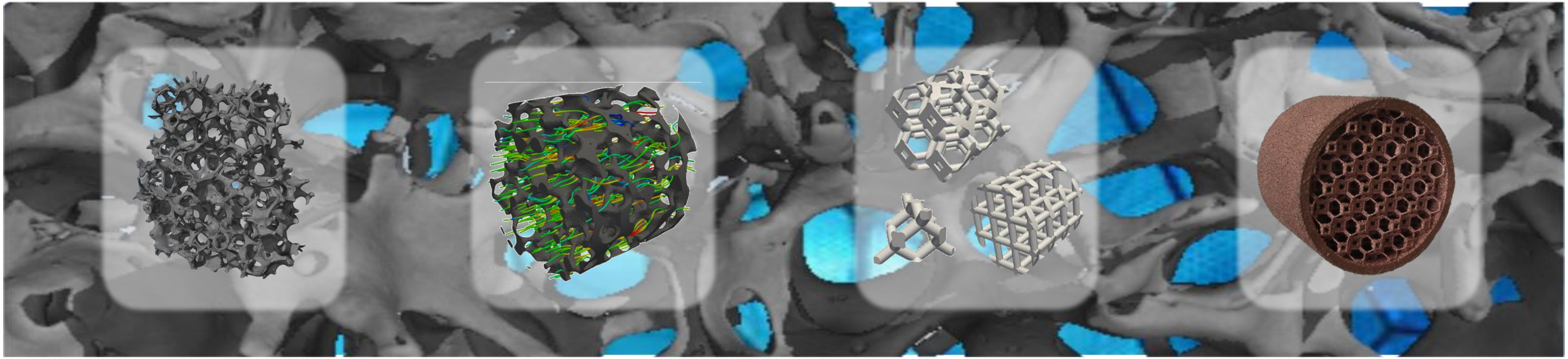
Hydrodynamics and heat transport in highly porous open-celled structures

Dr.-Ing. Benjamin Dietrich



Topics on cellular materials @ TVT

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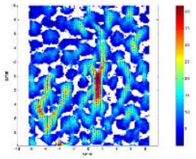
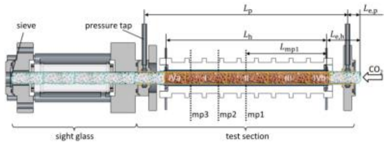
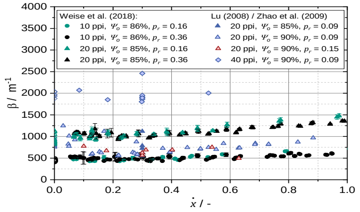
Experimental investigation

- single and multiphase flow
- pressure drop
- heat transfer coefficients
- heat conduction (effective thermal conductivity)
- flow distribution (via MRI)
- thermal radiation effects
- flow boiling of liquid CO_2

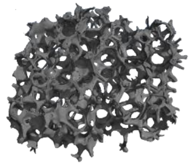






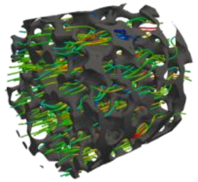
TVT

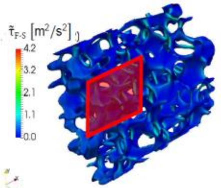
cellular structures

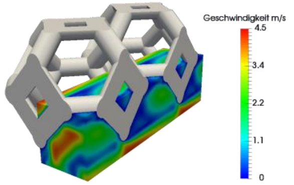


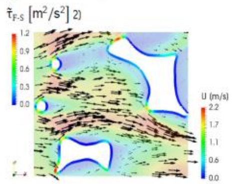
Numerical flow simulation

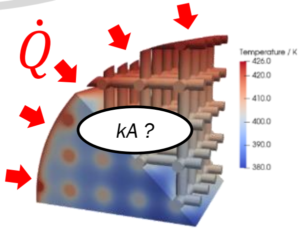
- single phase flow
- pressure drop
- heat transfer coefficients
- heat conduction (effective thermal conductivity)
- entrance effects
- flow regimes

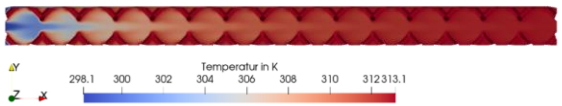












Main Funding

Federal Ministry for Economic Affairs and Climate Action

DFG

AiF

Federal Ministry of Education and Research

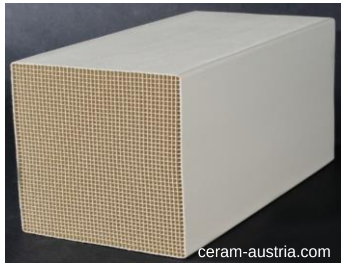
Friedrich und Elisabeth BOYSEN Stiftung für Forschung und Innovation

VECTOR STIFTUNG

Introduction

process intensification using structured internals → enhancement of heat and mass transfer

- honeycomb structrures



- packed beds

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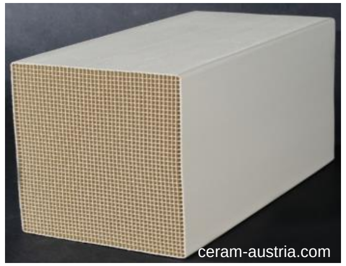
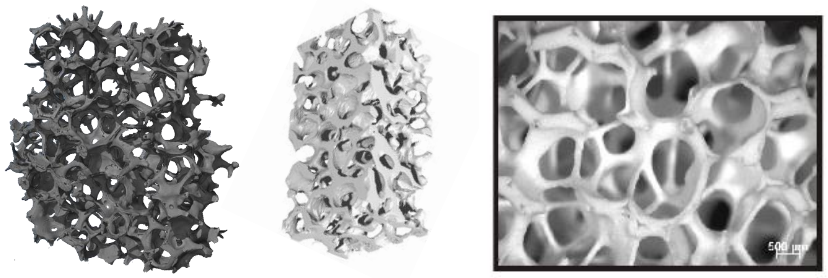


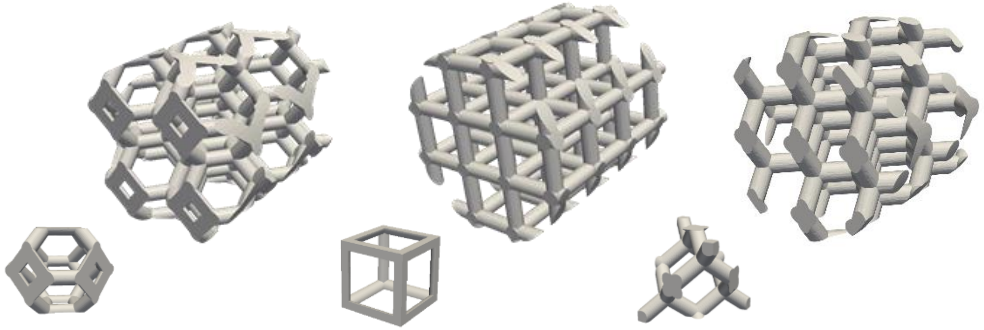
- packed beds

cellular structures

- open-celled foams/ sponges



- Periodic Open Cellular Structures (POCS)

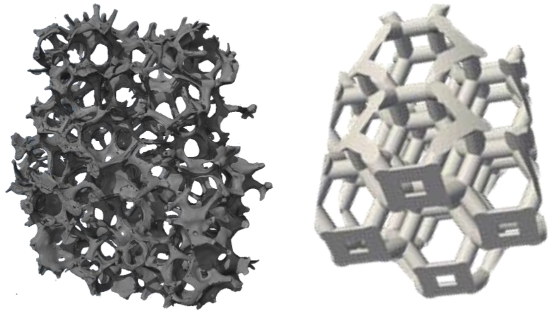


Introduction

properties of cellular structures

- high porosities
- large specific surface area
- continuous solid (and fluid) phase
- POCS: great design freedom

- acceptable pressure drop
- high heat transfer coefficients
- good heat conduction



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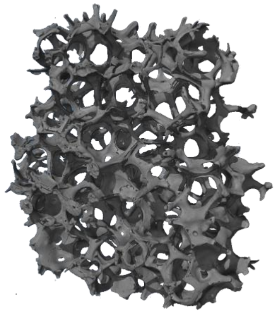
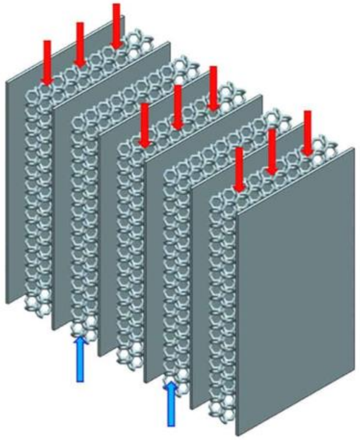


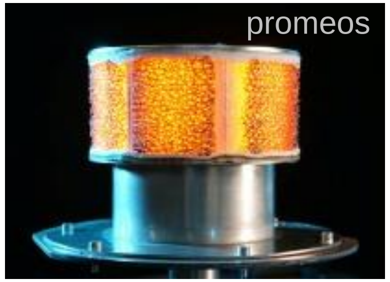
possible application fields

- chemical reactors
- light weight heat exchanger
- thermal and accustic insulation
- solar tower plant
- porous burner
- shock absorber



Ceramics.org

promeos



promeos

dlr

reuters

Introduction

designing process engineering systems

momentum transfer

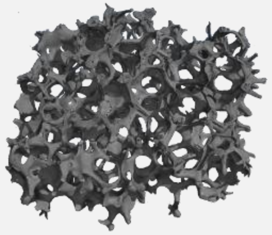
pressure drop

$\Delta p / \Delta L$

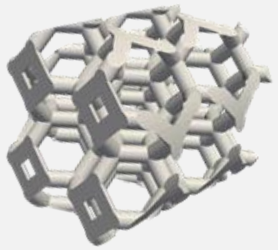
$$\left.\begin{matrix}\frac{\Delta p}{\Delta L}\\ h\end{matrix}\right\} = f\begin{pmatrix}\text{porosity,}\\ \text{unit cell,}\\ \text{cell design,}\\ \ldots\end{pmatrix} ?$$

heat transfer

heat transfer coefficient h



analogy between momentum and heat transfer (Generalized Lévêque Equation [1])



applicable for sponges and POCS?

1: H. Martin, Chem. Eng. Process. 35 (1996) 301-310

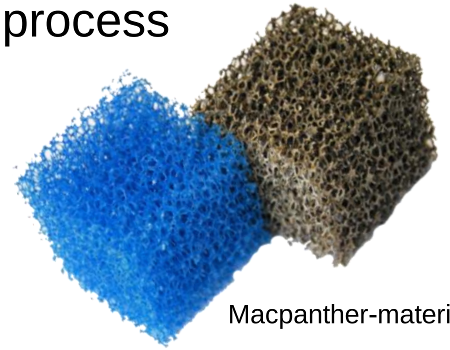
Sponge facts

characteristics

- typical cell densities: 5 … 45 ppi (pores per inch)
- typical porosities: 75 … 98 %
- stochastically random cell with broad size distribution
- many closed windows (= connecting faces between the cells)
- mass product, therefore comparatively cheap

manufacturing of sponges

- replica process
- casting process



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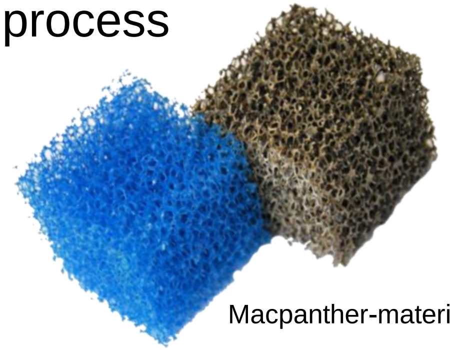


Macpanther-materials.de

initial situation

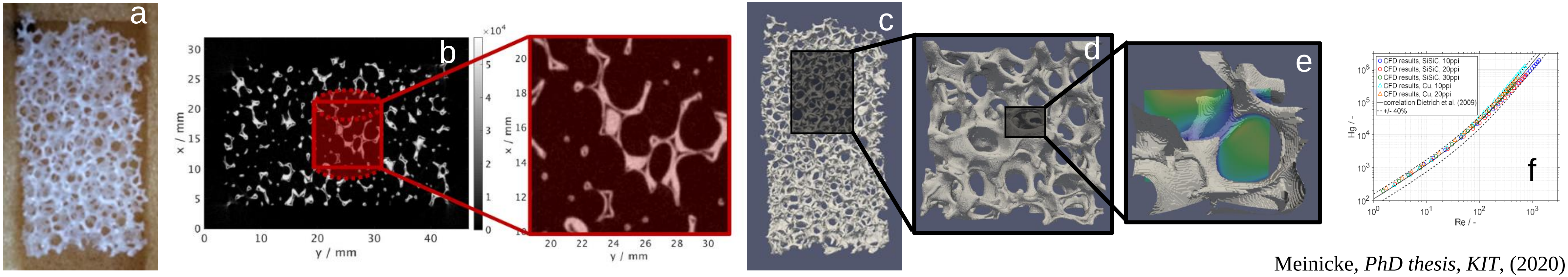
- correlations only available for certain sponge types, but no cross-type systematics
- findings for one type are not easily transferable to other types

➡ **one correlation for each transport property applicable to all unit cell typs is necessary**

Sponges – numerical procedure

numerical simulation using real sponge geometries

- original sponge sample (a)
- µCT measurement (b)
- geometrical reconstruction from µCT data (c)
- CFD modelling geometry and definition of REV (d)
- CFD data evaluation (e)
- validation by experimental data on identical sponge sample (f)



Meinicke, *PhD thesis*, *KIT*, (2020)

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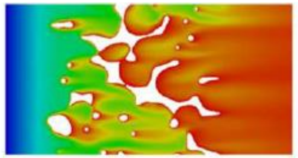
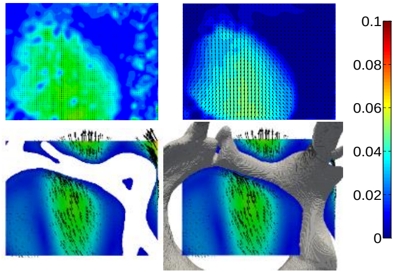
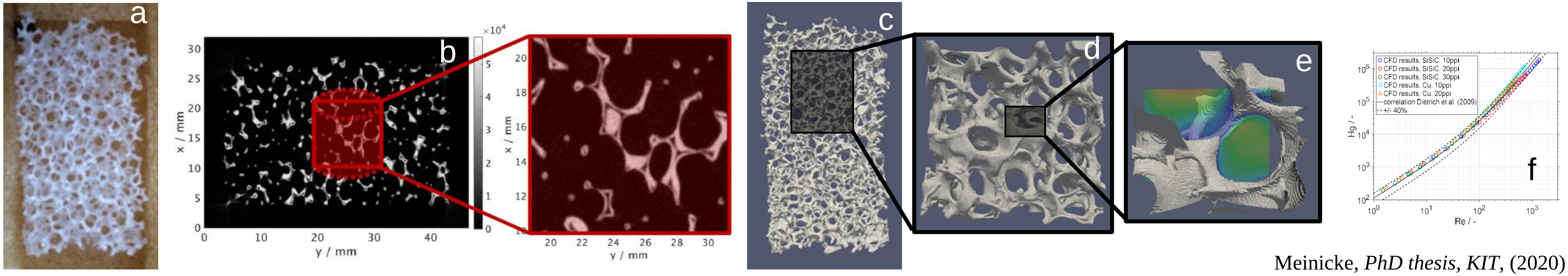
→ geometrical properties
→ heat transfer
→ pressure drop
→ flow regime characterisation



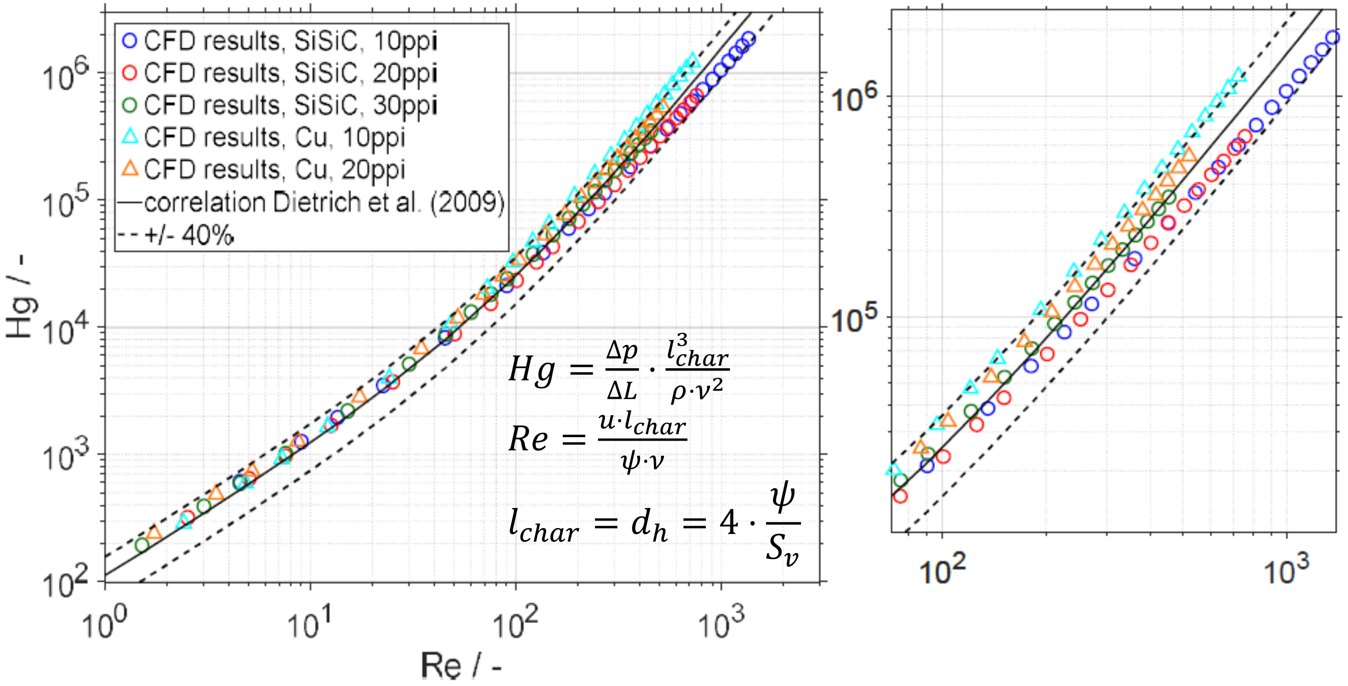


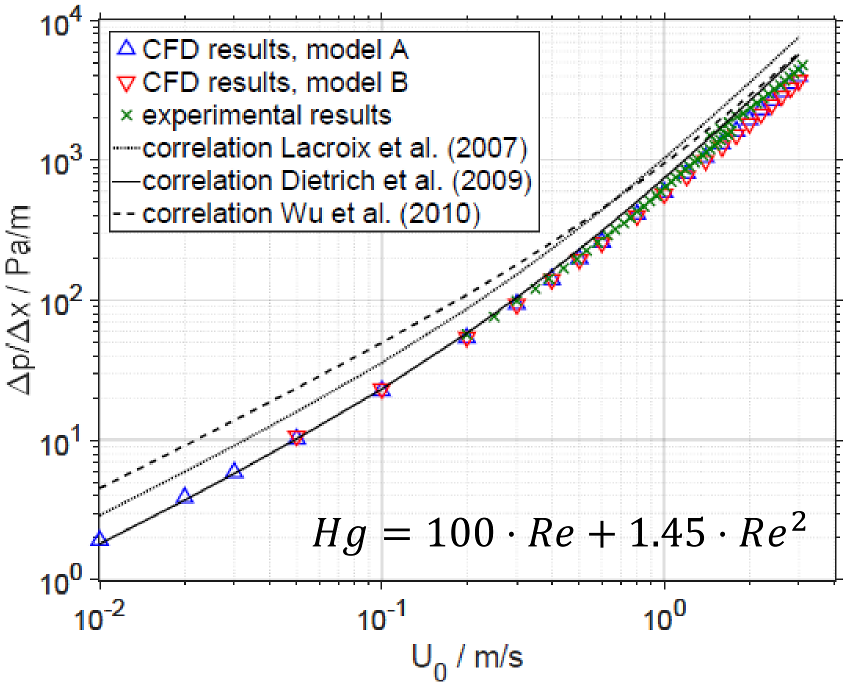


Meinicke, *PhD thesis*, *KIT*, (2020)

Sponges – pressure drop

comparison of numerical results to experimental data



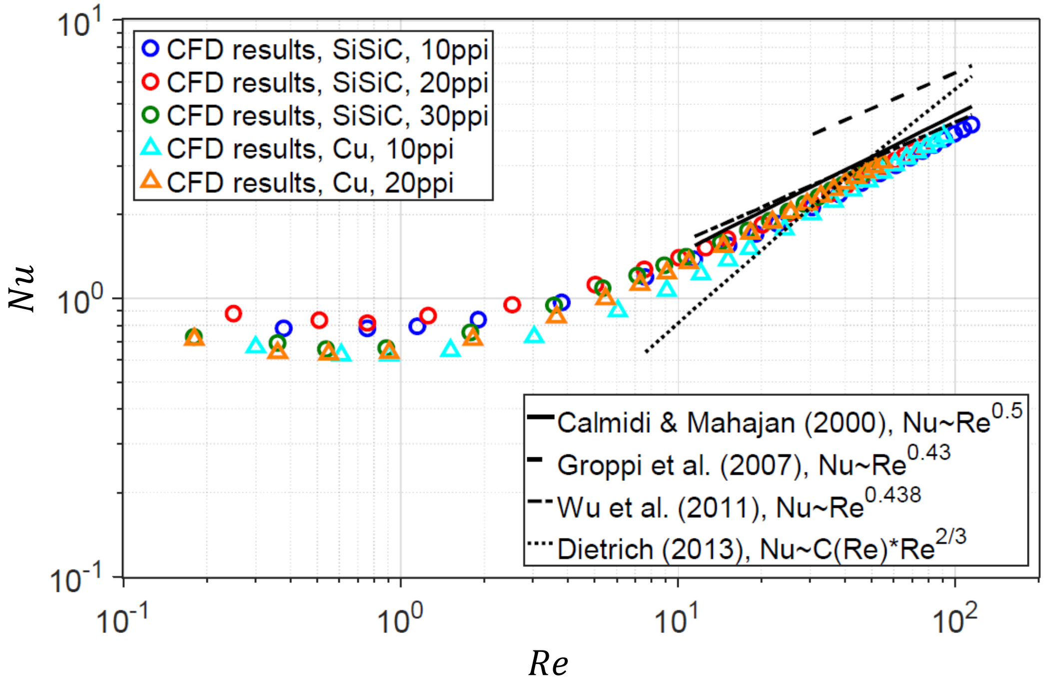


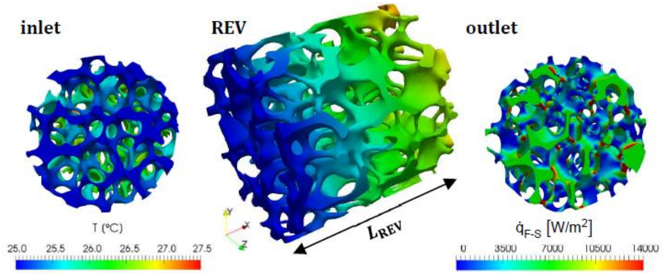
CFD results fit well to the own correlation achieved from experimental data

Meinicke, *PhD thesis*, *KIT*, (2020)

Sponges – heat transfer

heat transfer correlation based on CFD data





- low Re: nearly constant
- higher Re: $Nu \sim Re^n$
- CFD data correspond to experimental data

Nusselt number

$$Nu = \frac{h \cdot d}{k_F}$$

Reynolds number

$$Re = \frac{u_0 \cdot d}{\psi \cdot \nu_F}$$

d strut diameter

Meinicke, *PhD thesis, KIT*, (2020)

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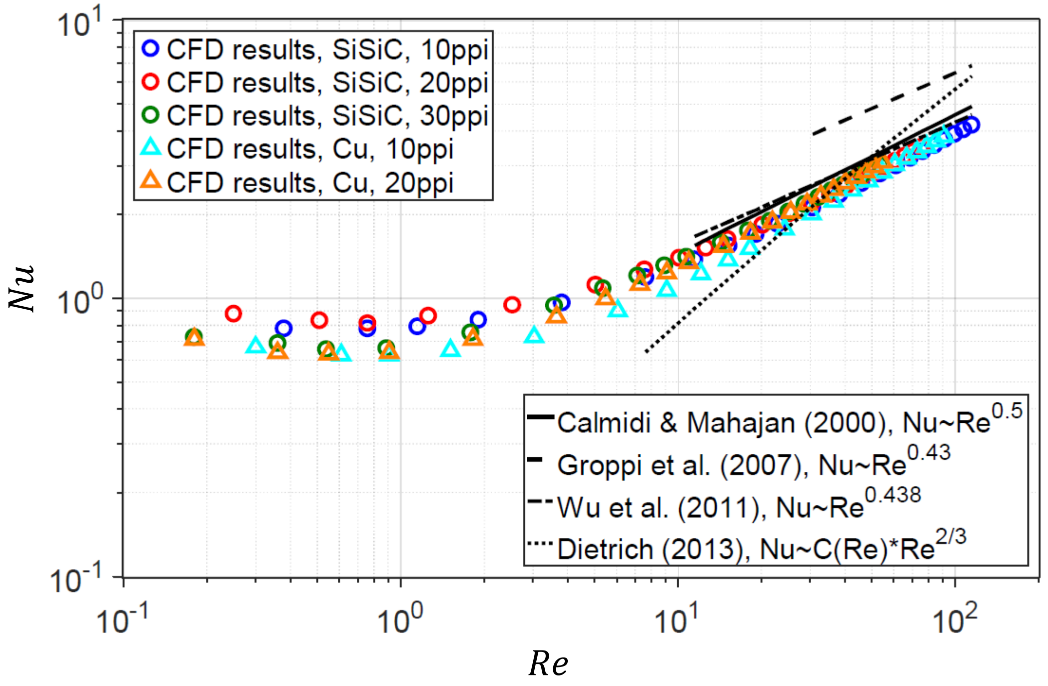

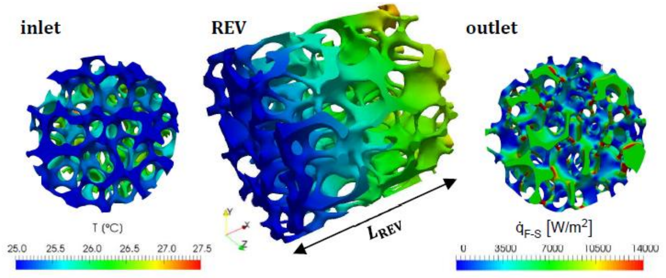

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d strut diameter

➡ data points for all sponge types coincide and can therefore be correlated

➡ $Nu = \sqrt[3]{Nu_{min,sp}^3 + (C_{lam} \cdot Re^{0.5})^3}$ with $Nu_{min,sp} = 0.71$ and $C_{lam} = 0.39$

Meinicke, *PhD thesis, KIT*, (2020)

Sponges – Generalized Lévêque Equation (GLE)

GLE = solution of velocity and temperature boundary layer equation for hydrodynamically developing flows by a similarity approach

$$h = C_{Le} \cdot \sqrt[3]{\frac{\tau \cdot Pr \cdot \rho_F \cdot k_F^3}{\mu_F^2 \cdot L_c}}$$

Nusselt number

$$Nu = \frac{h \cdot L_\mathrm{C}}{k_\mathrm{F}}$$

Hagen number

$$Hg = \frac{\Delta p \cdot L_\mathrm{C}^3}{L \cdot \rho_\mathrm{F} \cdot \nu_\mathrm{F}^2}$$

characteristic length

$$L_\mathrm{C} = \frac{\pi \cdot d}{2}$$

τ = local shear stress

Pr = Prandtl number

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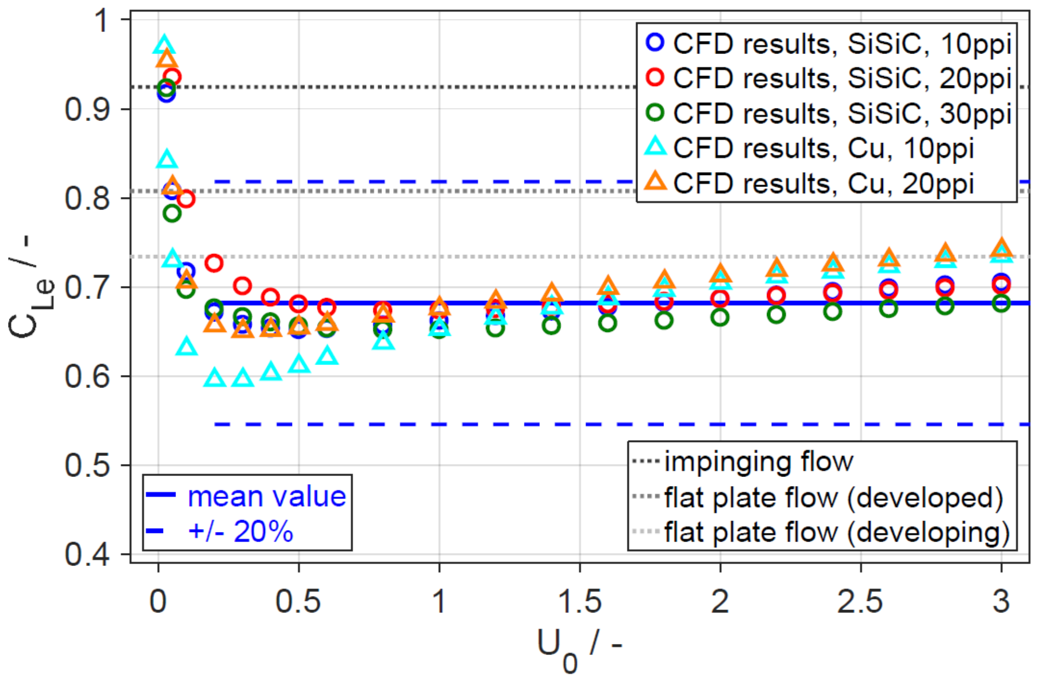

$$h = C_{Le} \cdot \sqrt[3]{\frac{\tau \cdot Pr \cdot \rho_F \cdot k_F^3}{\mu_F^2 \cdot L_c}}$$

- verified for different sponge types (variation of solid material, cell density)
- GLE applicable if $C_{Le} = const.$

Nusselt number

$$Nu = \frac{h \cdot L_\mathrm{C}}{k_\mathrm{F}}$$

Hagen number

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characteristic length

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τ = local shear stress

Pr = Prandtl number

➡ GLE valid for „higher“ superficial velocities, where axial heat conduction is neglectable

➡ **heat transfer coefficients of sponges estimable from corresponding $\Delta p / \Delta L$**

Meinicke, *PhD thesis*, *KIT*, (2020)

POCS – why particularly interesting?

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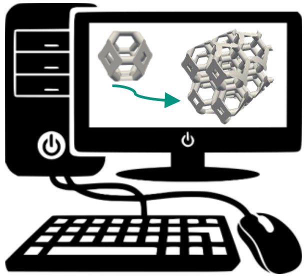
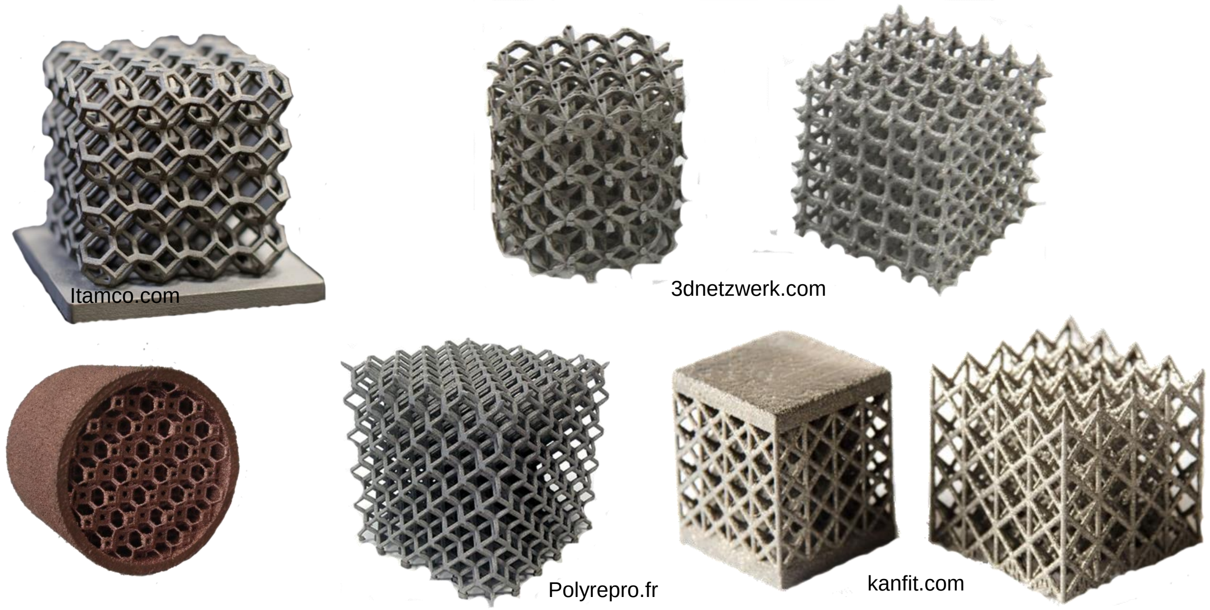
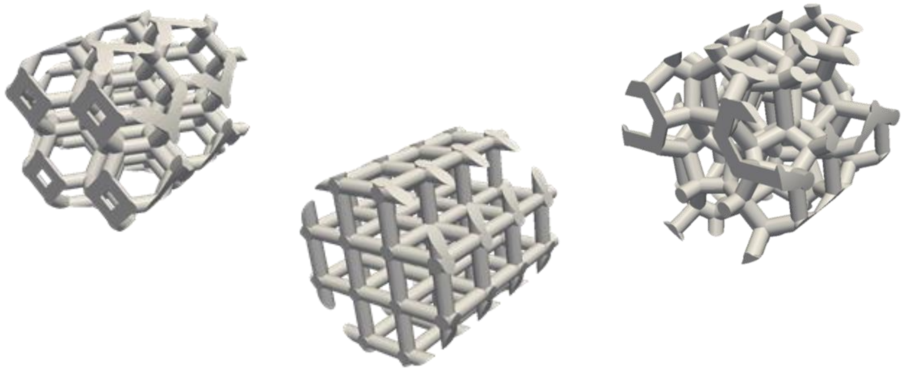
Manufacturing of POCS



Additive manufacturing





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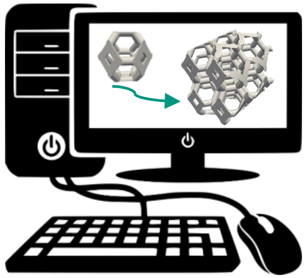

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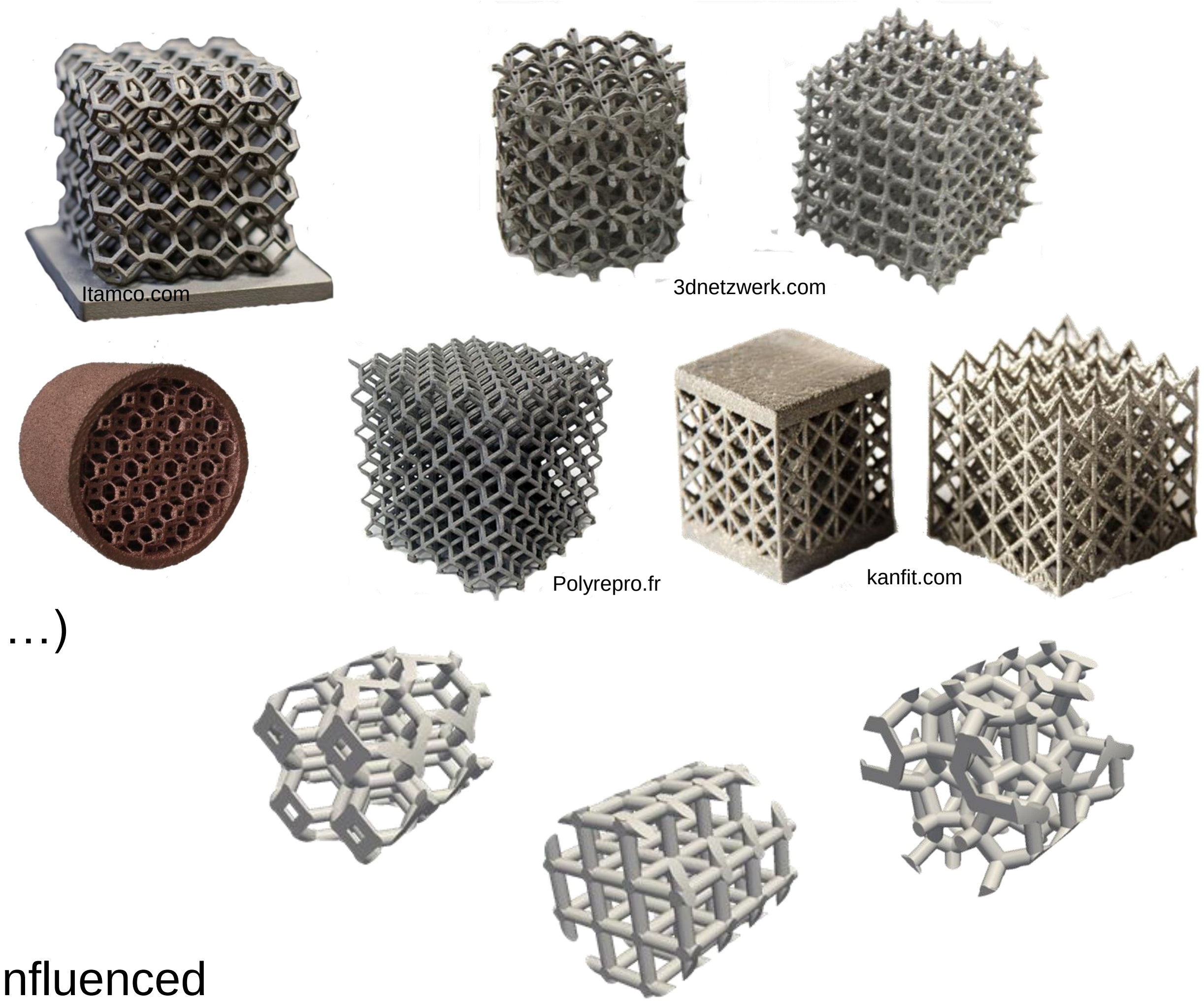


Advantages and Oppertunities

- large design freedom (unit cell, porosity, strut shape, …)
- variety of solid materials possible
- geometries can be adapted to the installation space
- direct wall connection possible

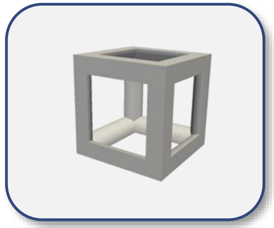
➔ hydrodynamics and heat transport can be directly influenced

POCS – heat transfer and pressure drop

initial situation

- correlations only available for certain unit cell geometries, but no cross-cell systematics!
- findings are not easily transferable
- prediction of arbitrary structures not reliable

➡ **one correlation for each transport property applicable to all unit cell typs is necessary**



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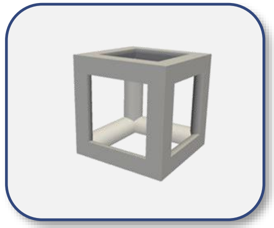

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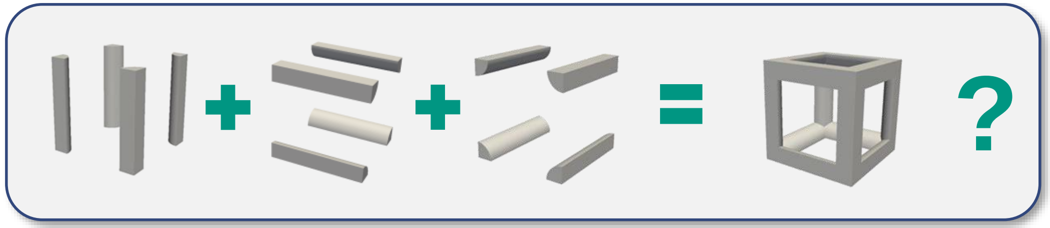
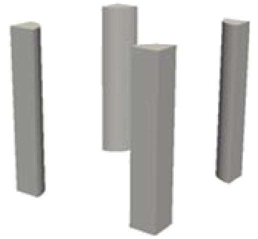
Hypothesis: Bottom – Up – Methology

- unit cells are a geometrical superposition of strut arrangements
- correlations possible using a superposition of the contributions of respective strut arrangements
- Advantages:
  - strut arrangements = simple geometries
  - validated correlations are available
  - procedure applicable for any POCS

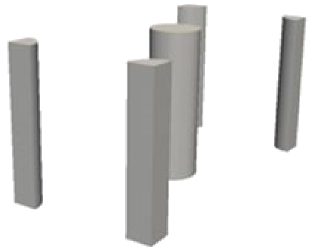


POCS – geometry specification

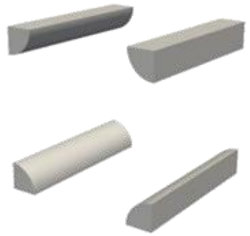
Struts



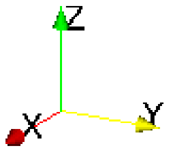
In-line struts



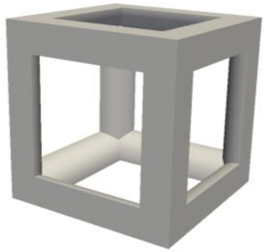
Staggered struts



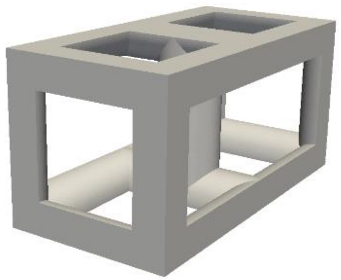
Inclined struts



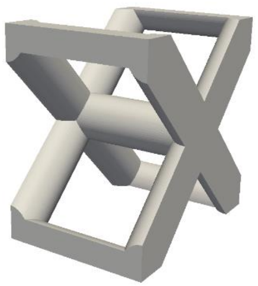
POCS



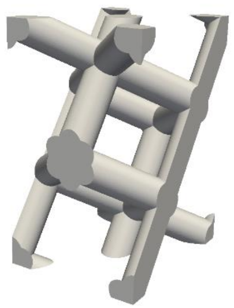
Cubic cell



Staggered cubic cell



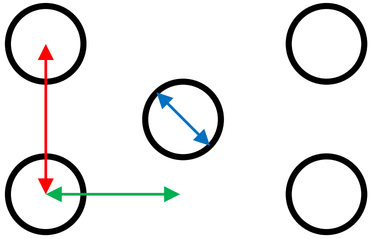
Inclined cubic cell

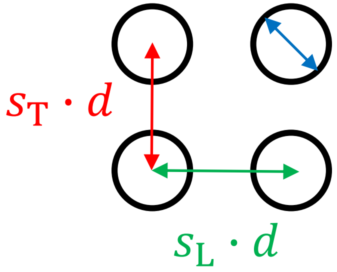


Double inclined cubic cell

strut diameter
$d = 0.64\ \mathrm{mm}$

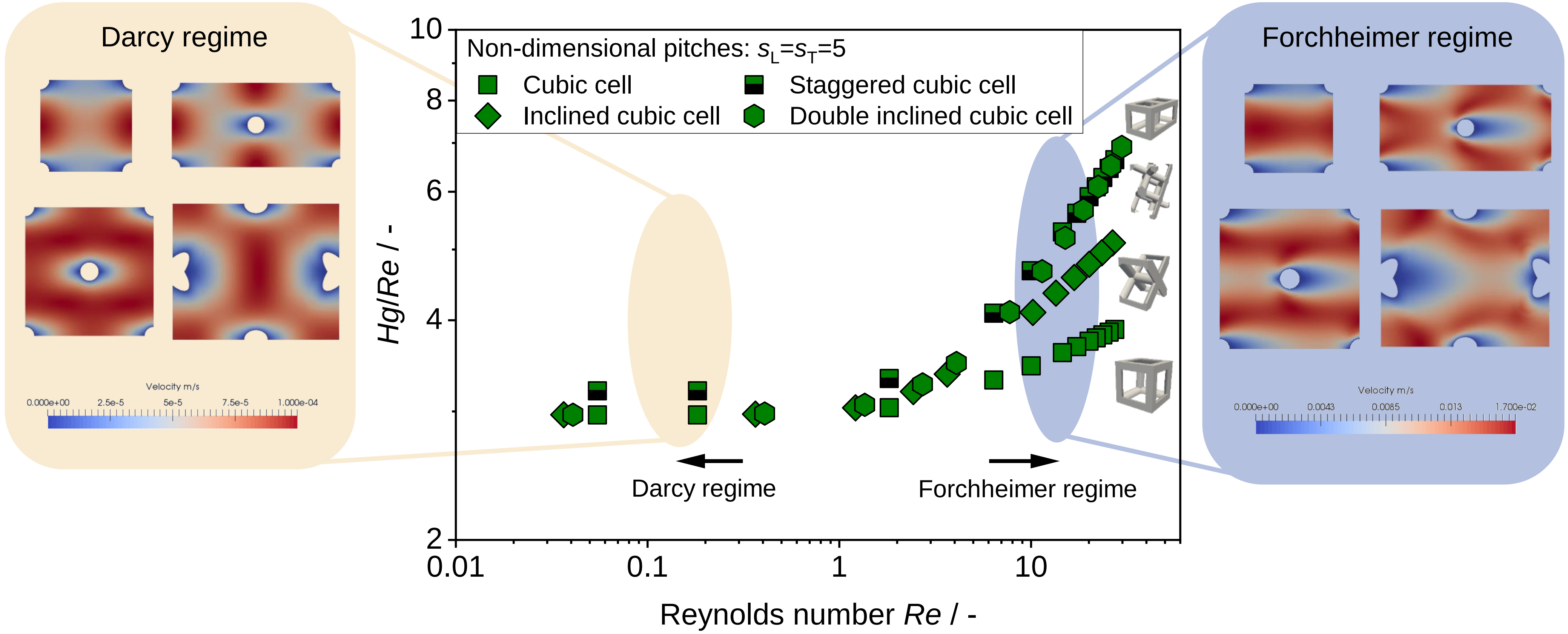
$s_\mathrm{T}, s_\mathrm{L} = \{2; 3; 4; 5\}$





Dubil et al., *Int. J. Heat Mass Transf.*, 200, 123546, (2023)

POCS – pressure drop



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characteristic length

$$L_C = \frac{\pi \cdot d}{2}$$

- linear (Darcy regime) and quadratic (Forchheimer regime) behavior
- significant influence of the unit cell geomentry on pressure drop in the Forchheimer regime

Dubil et al..
16th Int Conf Heat Transf Fluid Mech Thermodyn, (2022)

POCS – pressure drop

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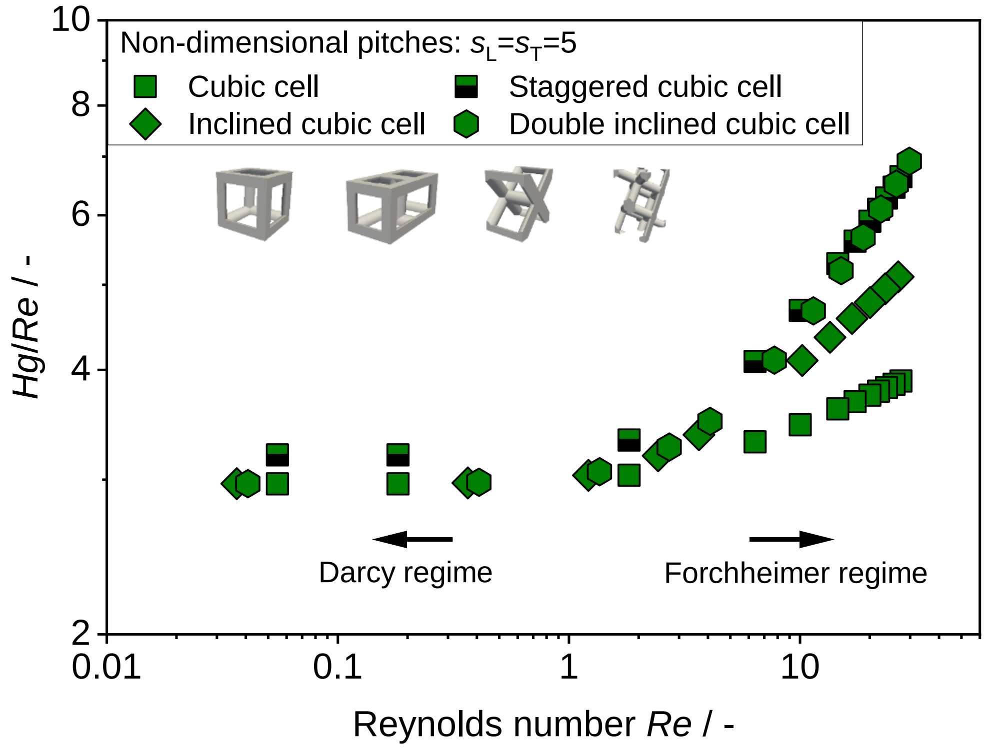
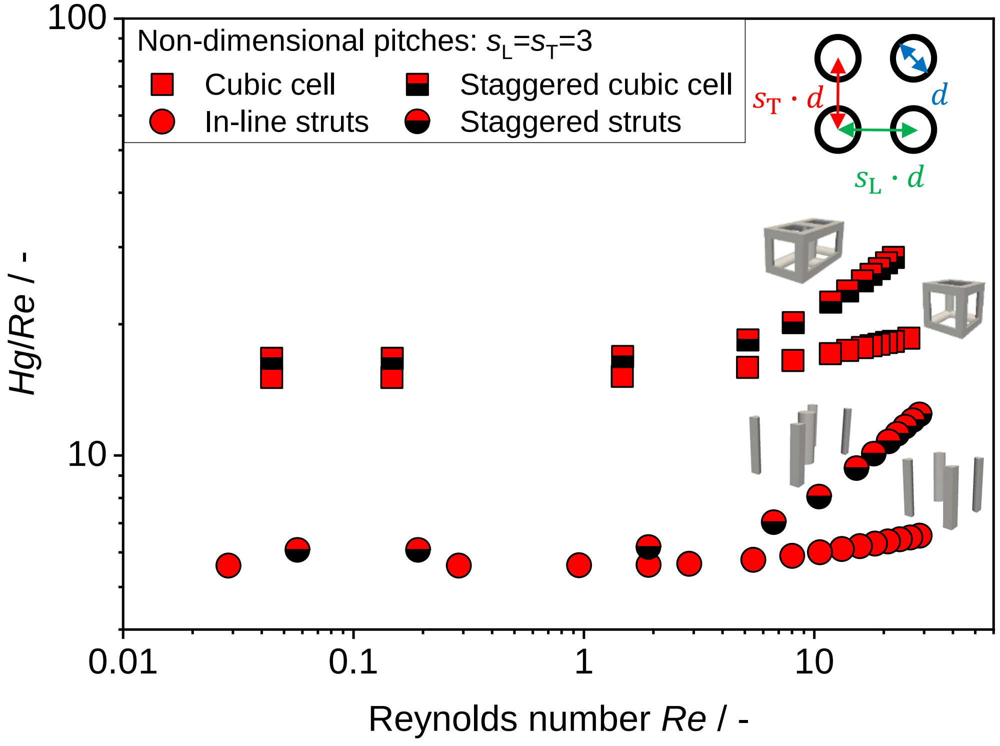




Hagen number

$$Hg = \frac{\Delta p \cdot L_C^3}{L \cdot \rho_F \cdot \nu_F^2}$$

Reynolds number

$$Re = \frac{u_0 \cdot L_C}{\psi \cdot \nu_F}$$

characteristic length

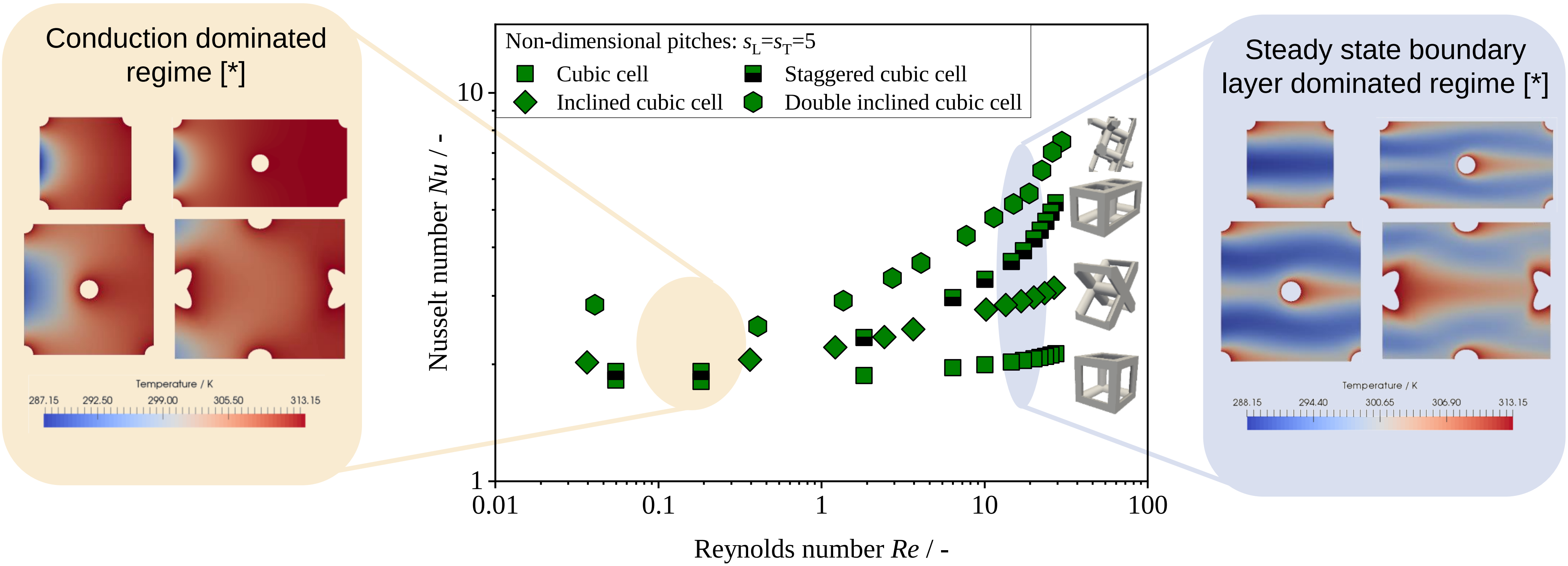
$$L_C = \frac{\pi \cdot d}{2}$$

- pressure drop increases when decreasing s_T due to decareasing porosity
- strut arrangements show same behaviour as corresponding POCS

Dubil et al.. *16th Int Conf Heat Transf Fluid Mech Thermodyn*, (2022)

POCS – heat transfer

Karlsruhe Institute of Technology



Nusselt number

$$Nu = \frac{h \cdot L_C}{k_F}$$

Reynolds number

$$Re = \frac{u_0 \cdot L_C}{\psi \cdot \nu_F}$$

characteristic length

$$L_C = \frac{\pi \cdot d}{2}$$

- nearly constant behavior at low Re and $Nu \sim Re^n$ for higher Re
- orientation of the cubic cell has influence on heat transfer

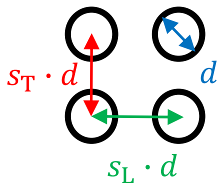
*Meinicke et al., *Int. J. Heat Mass Transf.*,149, 119201 (2019)
Dubil et al.. *16th Int Conf Heat Transf Fluid Mech Thermodyn*, (2022)

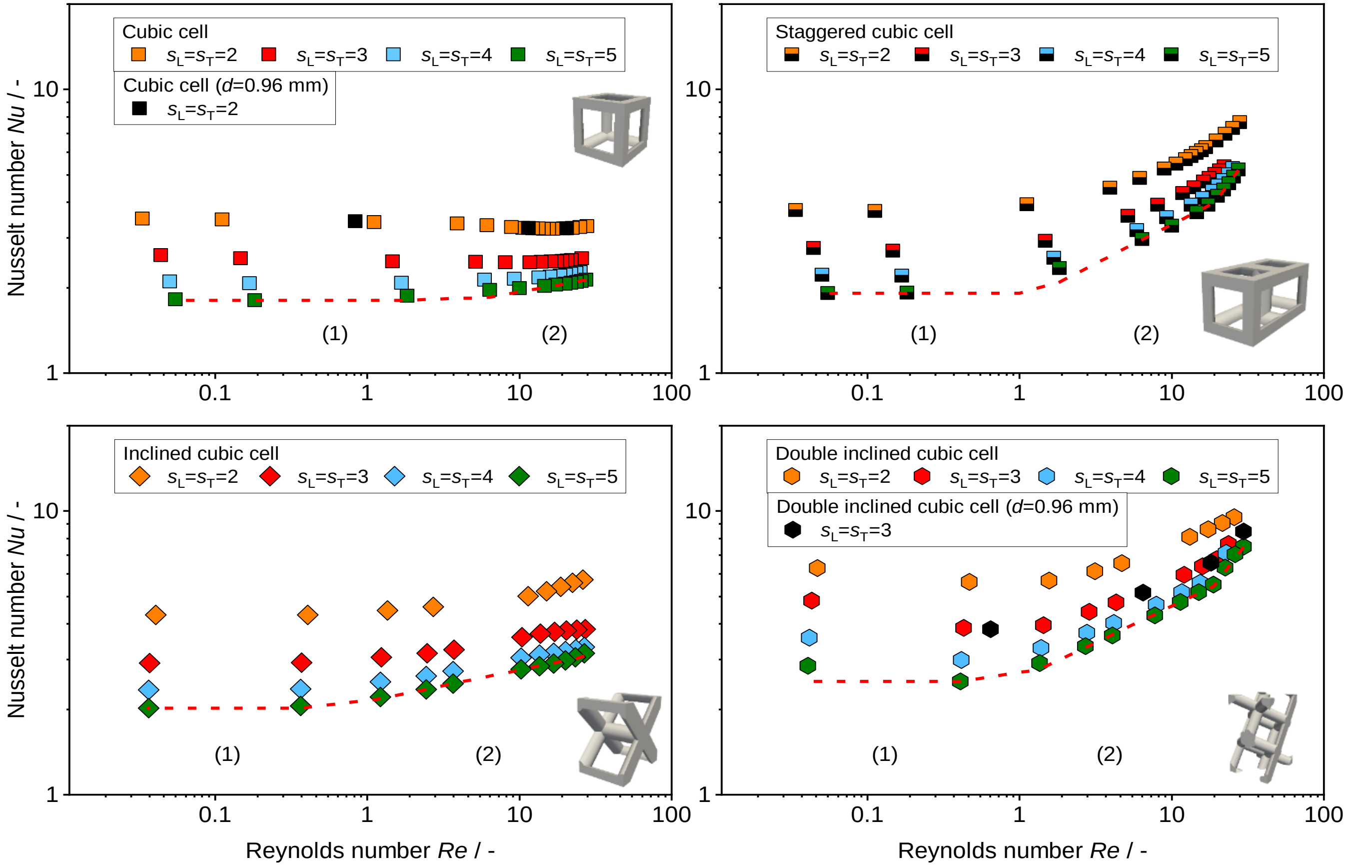
POCS – heat transfer

Karlsruhe Institute of Technology

Different Regimes [*]:

- Conduction dominated regime (1)
- Steady-state boundary layer dominated regime (2)





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Reynolds number

$$Re = \frac{u_0 \cdot L_C}{\psi \cdot \nu_F}$$

characteristic length

$$L_C = \frac{\pi \cdot d}{2}$$

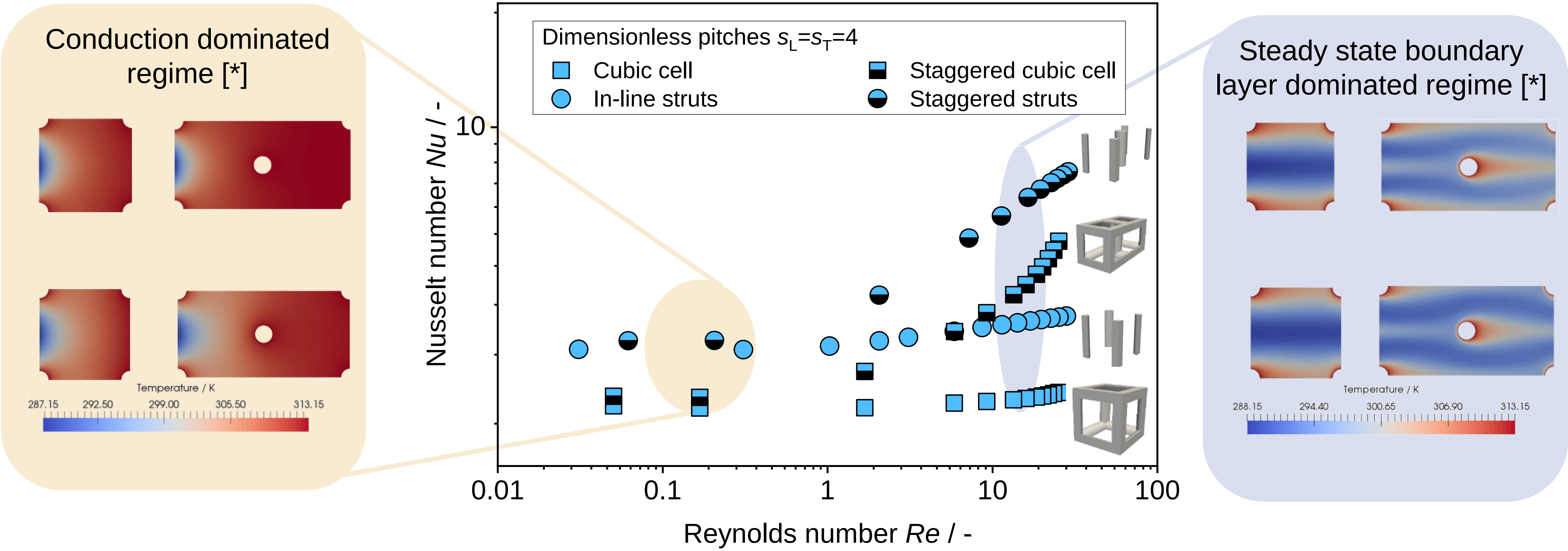
➡ distance (pitches) of the struts to each other influences heat transfer

➡ Can the observed differences between the unit cell geometries be quantified?

*Meinicke et al., *Int. J. Heat Mass Transf.*,149, 119201 (2019)

Dubil et al., *Int. J. Heat Mass Transf.*, 200, 123546, (2023)

POCS – heat transfer



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characteristic length

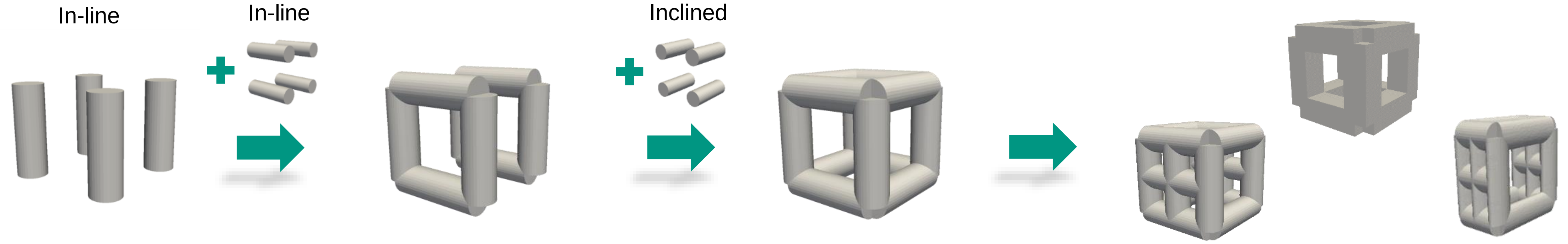
$$L_C = \frac{\pi \cdot d}{2}$$

- strut arrangement influences heat transfer
- strut arrangements show same behavior as corresponding POCS

*Meinicke et al., *Int. J. Heat Mass Transf.*,149, 119201 (2019)
Dubil et al., *Int. J. Heat Mass Transf.*, 200, 123546, (2023)

POCS – Bottom-Up Modeling Approach

Correlation of transport properties of any cells by a superposition of their structure-forming unit cells



Dubil et al., *Int. J. Heat Mass Transf.*, 200, 123546, (2023)   Dubil et al.. *16th Int Conf Heat Transf Fluid Mech Thermodyn*, (2022)

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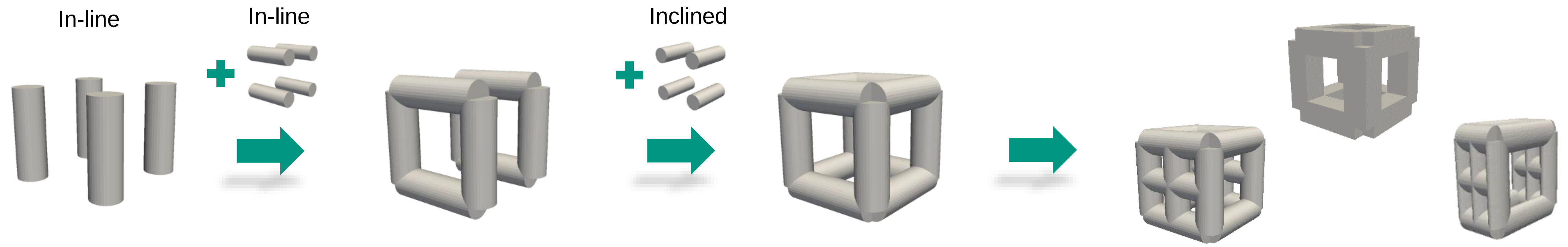


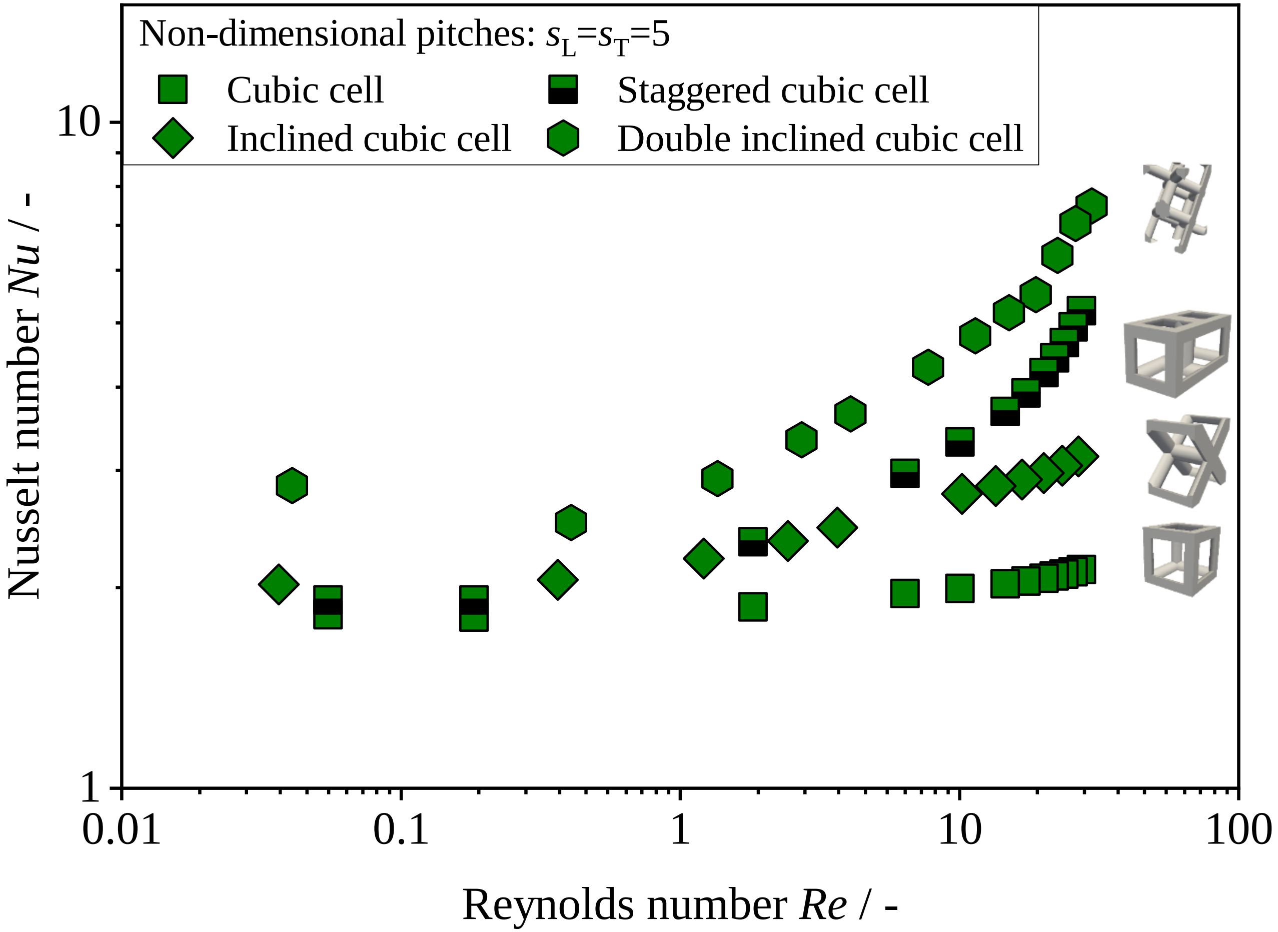
Mathematical procedure

- Nusselt number $Nu_{\text{Cell}} = \sum_{i=1}^{N_{\text{Arr}}} Nu_i \cdot \frac{A_i}{A_{\text{Cell}}} \cdot f_{\text{Proj},i}$
- Hagen number $Hg_{\text{Cell}} = \sum_{i=1}^{N_{\text{Arr}}} Hg_i \cdot N_i$
  - surface area of each strut arrangement $A_i = f_{\text{Node}} \cdot \pi \cdot d \cdot L \cdot N_{\text{Strut},i}$
  - factors $f_{\text{Proj}} = \begin{cases} \frac{2}{\pi} & \text{, Inclined struts} \\ 1 & \text{, In} - \text{line and staggered struts} \end{cases}$

$$f_{\text{Node}} = \begin{cases} 0.417\ , s_T = s_L = 2 \\ 0.559\ , s_T = s_L = 3 \\ 0.632\ , s_T = s_L = 4 \\ 0.678\ , s_T = s_L = 5 \end{cases}$$

Dubil et al., *Int. J. Heat Mass Transf.*, 200, 123546, (2023)
Dubil et al.. *16th Int Conf Heat Transf Fluid Mech Thermodyn*, (2022)

POCS – Bottom-Up Modeling Approach



Nusselt number

$$Nu = \frac{h \cdot L_C}{k_F}$$

Reynolds number

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characteristic length

$$L_C = \frac{\pi \cdot d}{2}$$

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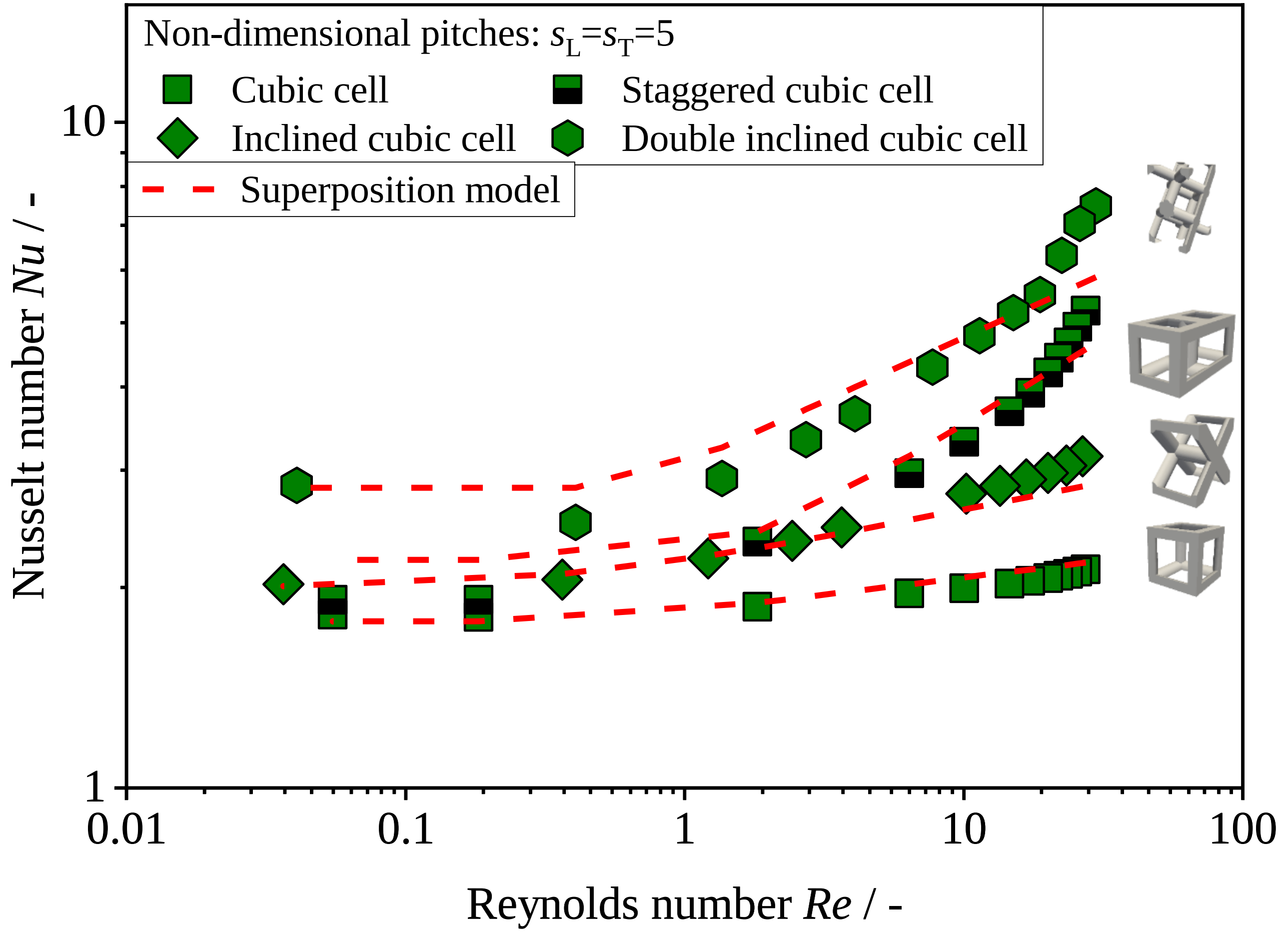

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Reynolds number

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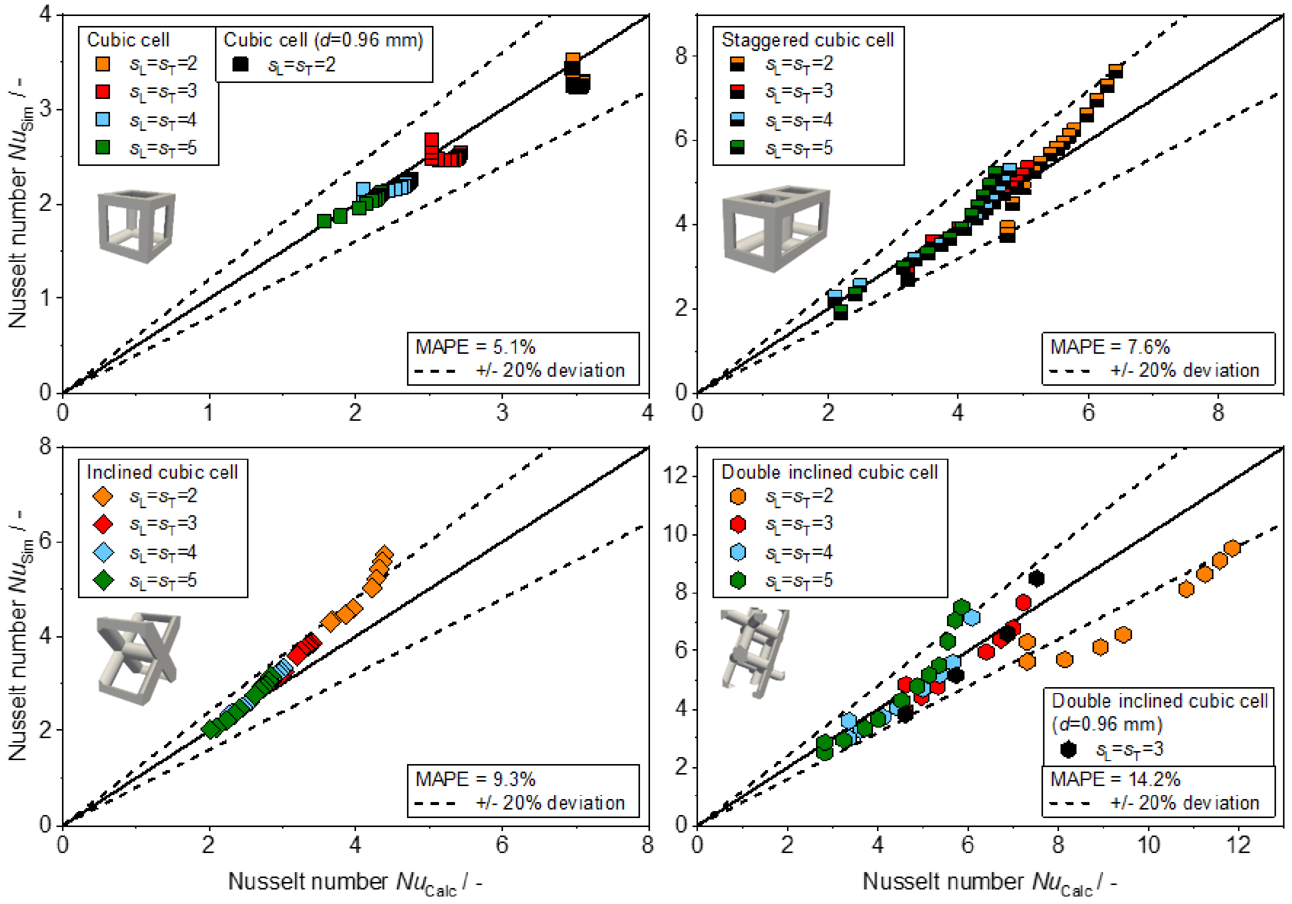
characteristic length

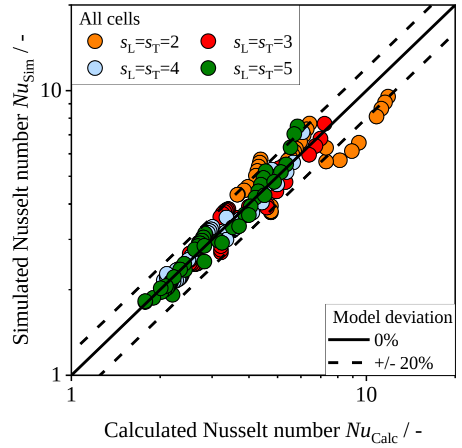
$$L_C = \frac{\pi \cdot d}{2}$$

➡ good agreement of simulation results with model for steady flow

Dubil et al., *Int. J. Heat Mass Transf.*, 200, 123546, (2023)
Dubil et al.. *16th Int Conf Heat Transf Fluid Mech Thermodyn*, (2022)

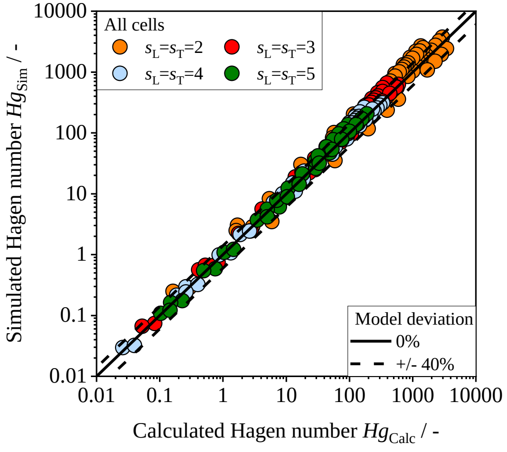
POCS – Bottom-Up Modeling Approach





$APE < 20\% = 92\%$

$MAPE = 15\%$



$APE < 40\% = 88\%$

$MAPE = 21\%$

model approach applicable for all investigated unit cells

Dubil et al., *Int. J. Heat Mass Transf.*, 200, 123546, (2023)
Dubil et al.. *16th Int Conf Heat Transf Fluid Mech Thermodyn*, (2022)

POCS – Generalized Lévêque Equation (GLE)

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$$\mathrm{Nu} = C_{Le} \cdot \sqrt[3]{x_{fric} \cdot Hg \cdot Pr \cdot \frac{2}{S_v \cdot \pi \cdot d}}$$

- Check for different unit cells with different $s_L = s_T$ - values
- GLE applicable if $C_{Le} \; = \; const.$

Nusselt number

$$Nu = \frac{h \cdot L_C}{k_F}$$

Hagen number

$$Hg = \frac{\Delta p \cdot L_C^3}{L \cdot \rho_F \cdot \nu_F^2}$$

characteristic length

$$L_C = \frac{\pi \cdot d}{2}$$

x_{fric} = friction factor

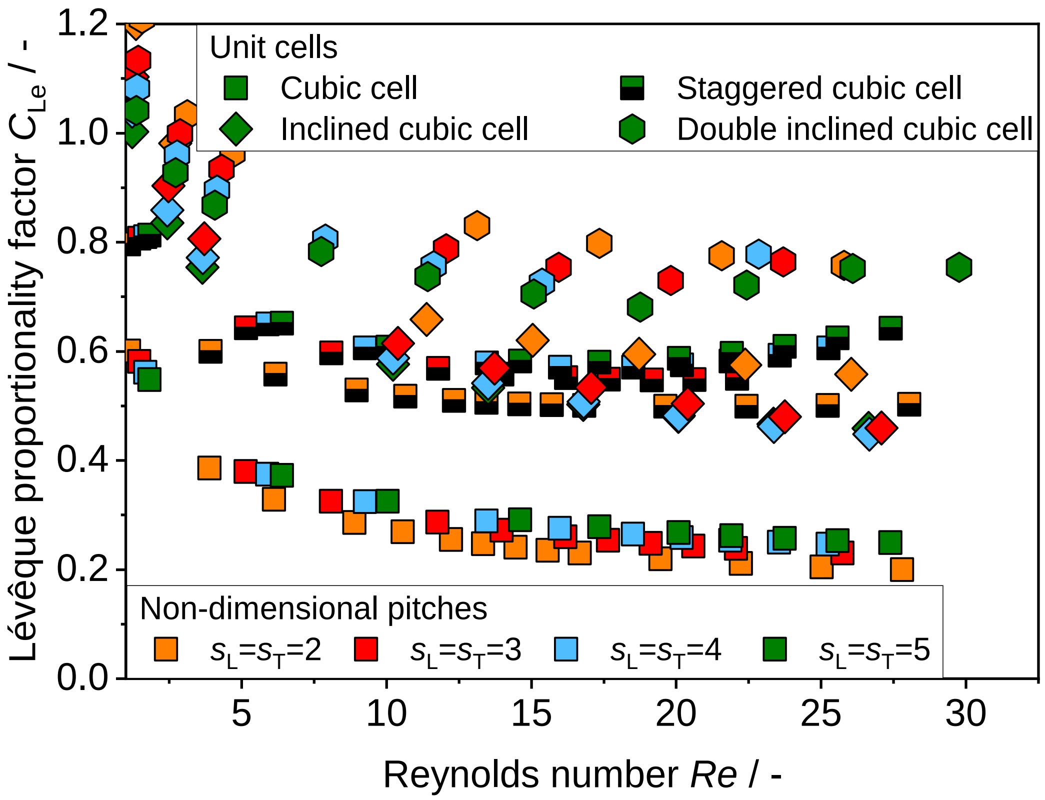
S_v= spec. surf. area

Pr = Prandtl number

Dubil et al.. *16th Int Conf Heat Transf Fluid Mech Thermodyn*, (2022)

POCS – Generalized Lévêque Equation (GLE)

Karlsruhe Institute of Technology



$$\mathrm{Nu} = C_{Le} \cdot \sqrt[3]{x_{fric} \cdot Hg \cdot Pr \cdot \frac{2}{S_v \cdot \pi \cdot d}}$$

- Check for different unit cells with different $s_L = s_T$ - values
- GLE applicable if $C_{Le} = const.$

Nusselt number

$$Nu = \frac{h \cdot L_C}{k_F}$$

Hagen number

$$Hg = \frac{\Delta p \cdot L_C^3}{L \cdot \rho_F \cdot \nu_F^2}$$

characteristic length

$$L_C = \frac{\pi \cdot d}{2}$$

x_{fric} = friction factor

S_v= spec. surf. area

Pr = Prandtl number

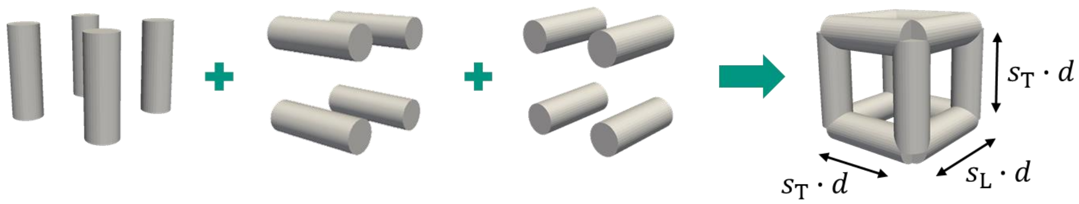
➡ GLE valid for „higher“ Reynolds number, where axial heat conduction is neglectable

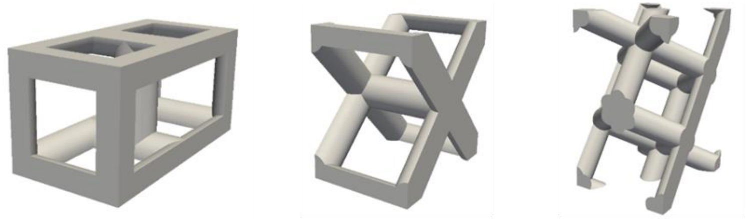
➡ heat transfer coefficients of POCS estimable from corresponding pressure drop

Dubil et al.. *16th Int Conf Heat Transf Fluid Mech Thermodyn*, (2022)

Summary

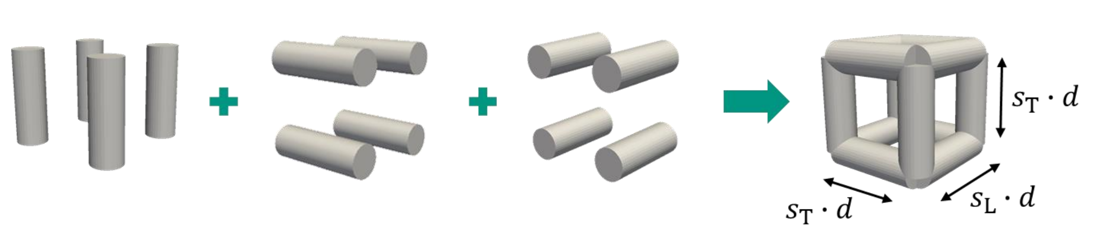
Hypothesis: transport parameters of complex cells (POCS) can be described as a superposition of the contributions of their respective strut arrangements

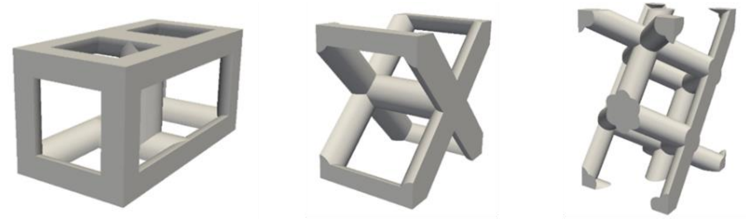




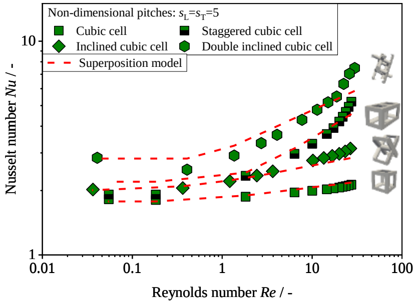
Summary

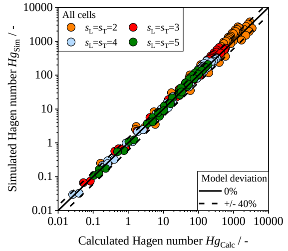
Hypothesis: transport parameters of complex cells (POCS) can be described as a superposition of the contributions of their respective strut arrangements

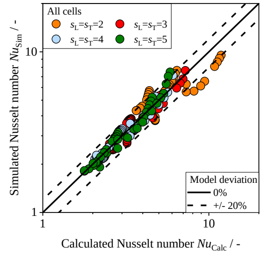




- strut arrangement significantly influences transport properties
- similar curve progressions for POCS and equivalent strut arrangements
- Hagen and Nusselt number as a function of Reynolds number of different cubic cells is well correlatable using one model approach



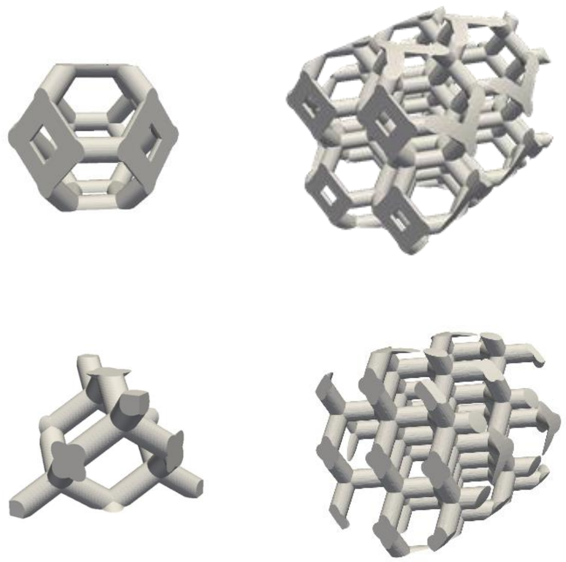


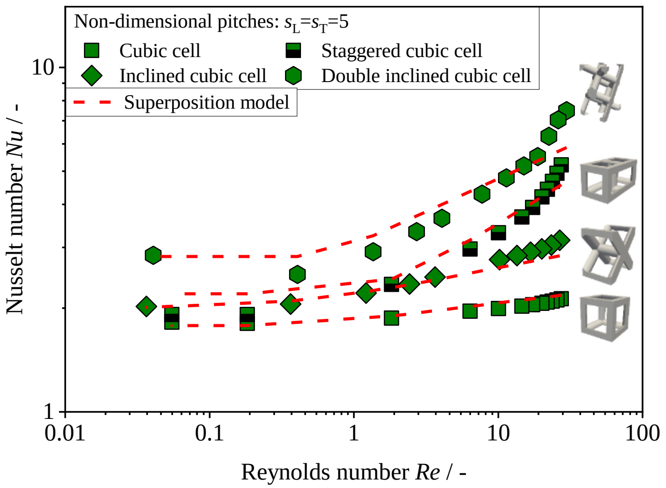


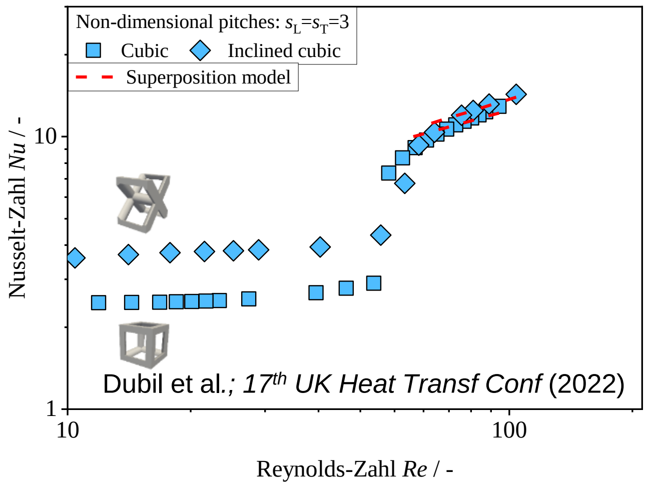
Hypothesis is verified for investigated cubic cells

Outlook – current works

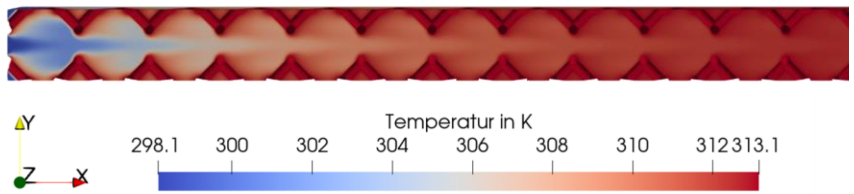
- Bottom-Up-Approach applicable for other types and complex structures?
- Bottom-Up-Approach applicable to unsteady flow?







- Thermal and hydrodynamic entrance length

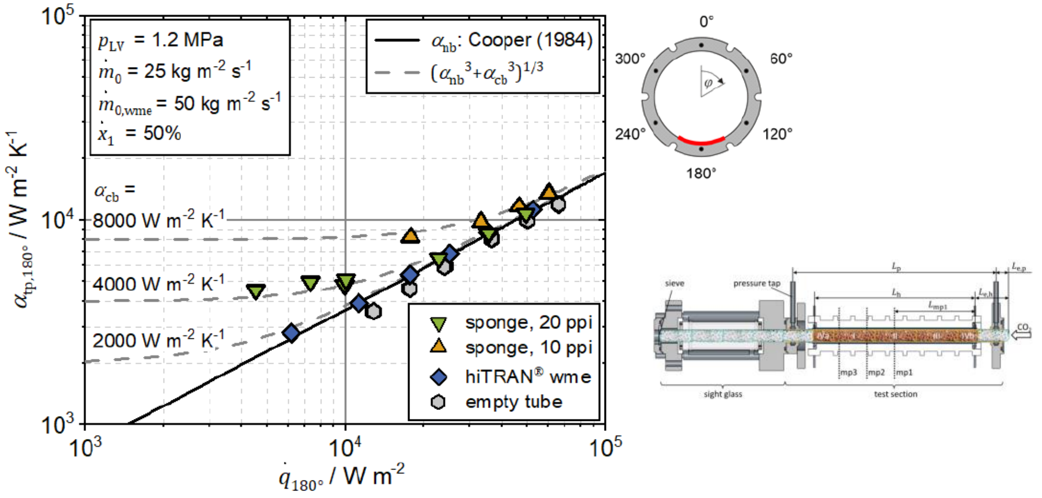


Knapp et al.; *Dechema Fachgruppentreffen WuS* (2023)

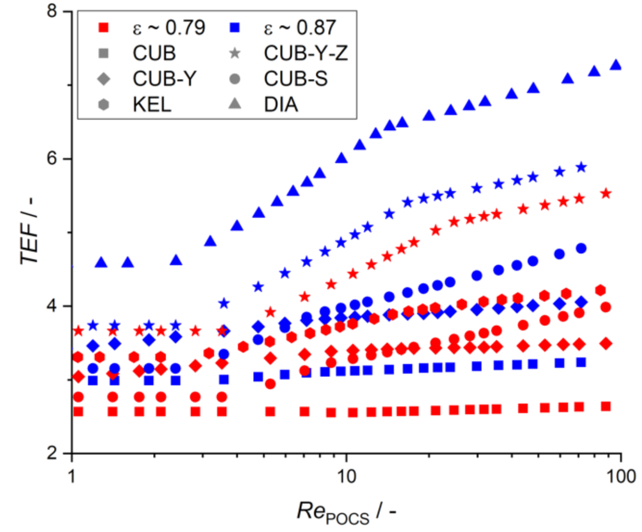
Outlook – current works

- characterization of the structure performance
  - Theoretical: Thermal Enhancement Factor (TEF) → IHTC-17 | ID: 0064
  - Experimental: - Use as compact light weight heat exchanger for hybrid aircrafts

    - Use in flow boiling of liquid CO_2



Haertlé, *PhD thesis, KIT*, (2022)



Knapp et al., *IHTC-17* | *ID: 0064*

Many thanks to …

- … you for your attention!
- … my PhD-students Jonas Bender, Konrad Dubil, Sonja Haertlé, Katharina Knapp, Sebastian Meinicke
  for their excellent work!
- … German Reseach Foundation (DFG),

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DFG

Friedrich und Elisabeth
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