Influence of the shape of the strut cross section on the hydrodynamics and heat transfer of laminar steady-state flow in Kelvin cells

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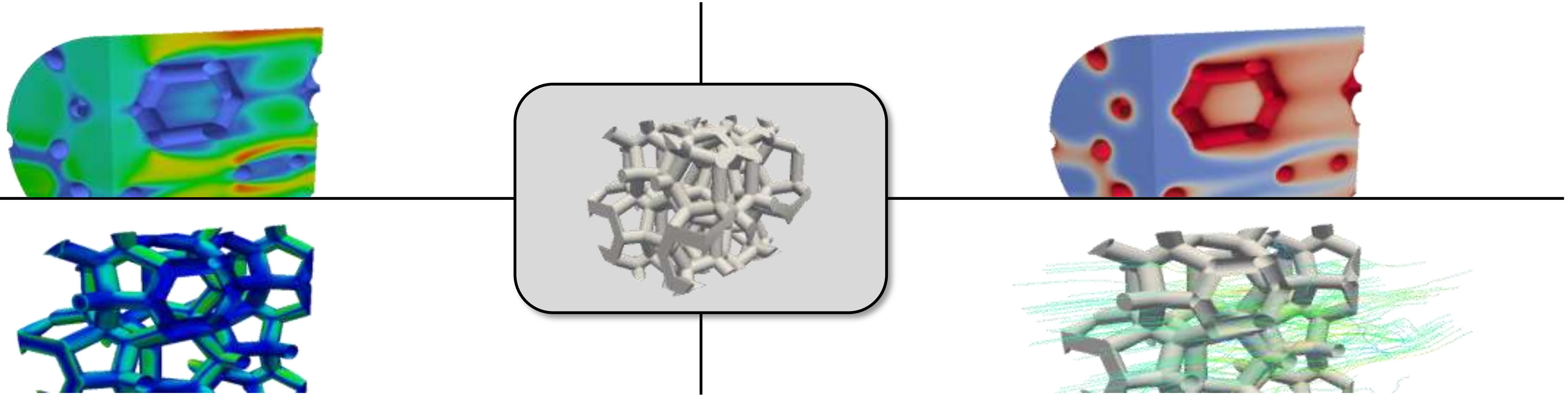


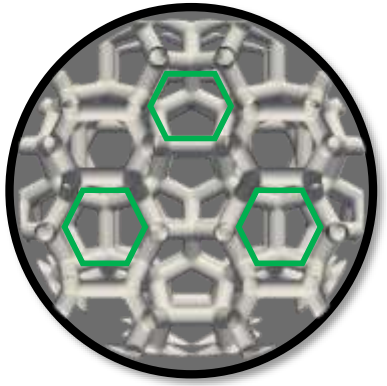
Introduction

Periodic Open Cellular Structures (POCS)

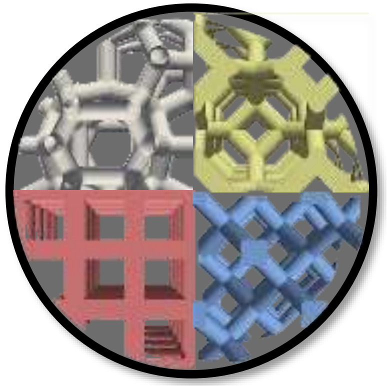
- Continuous solid and fluid phase
- Periodic arrangement of unit cells
- High variability of the unit cell geometry
- Low pressure drop with comparatively good heat transfer properties

Continuous
solid structure

High heat
transfer coefficients



Large
specific surface area

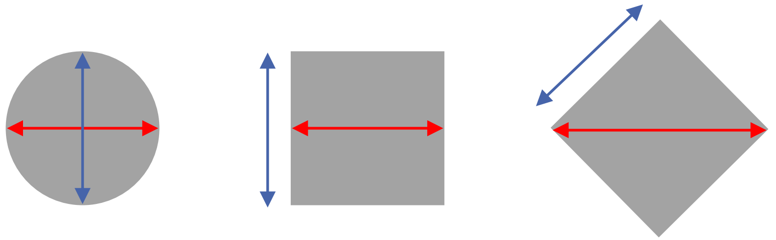


Great design freedom

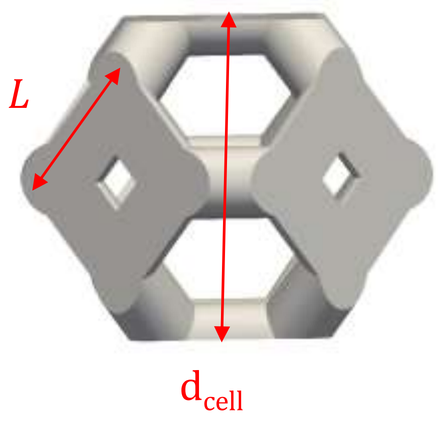
Geometry Specifications

- Kelvin unit cell with three different strut shapes: Circular, Square and Rotated Square (45^o)
- Unit cells with porosities 0.6 to 0.9 with increments of 0.05 generated
- Cell size determined from geometric models [1], [2] to achieve the reqiured porosity
- Inherent limitation in generating Kelvin cells: $d_{cell} > 2\sqrt{2}\ d_s$

Strut Dimension = 0.64 mm



d_s = 0.64 mm d_s = 0.64 mm $d_s = 0.64\sqrt{2}$ mm



$$L > d_s$$
$$L = \frac{d_{cell}}{2\sqrt{2}}$$

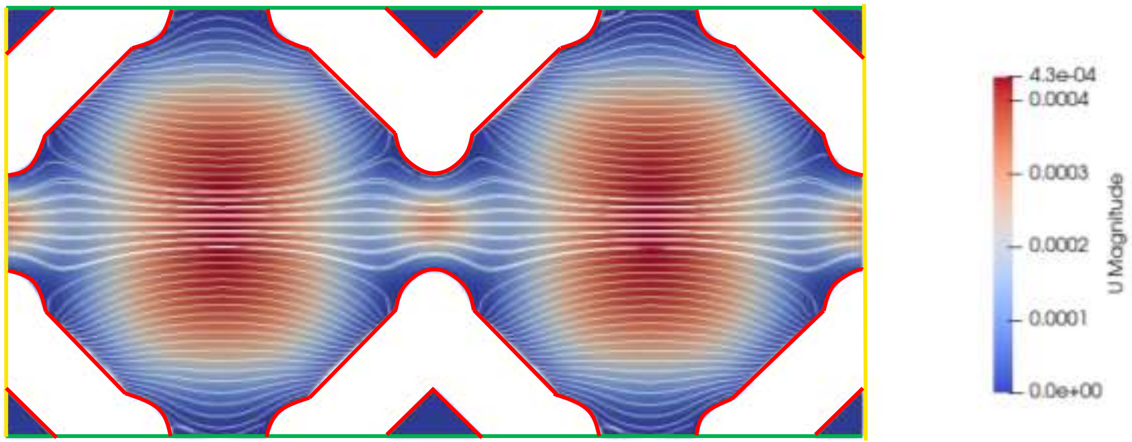
Circular Struts   Square Struts   Rotated Square Struts

[1] Kumar and Topin, Transport in Porous Media 105 (2014) [2] Ferroni et al, Industrial & Engineering Chemistry Research 60 (2021)

Numerical Setup

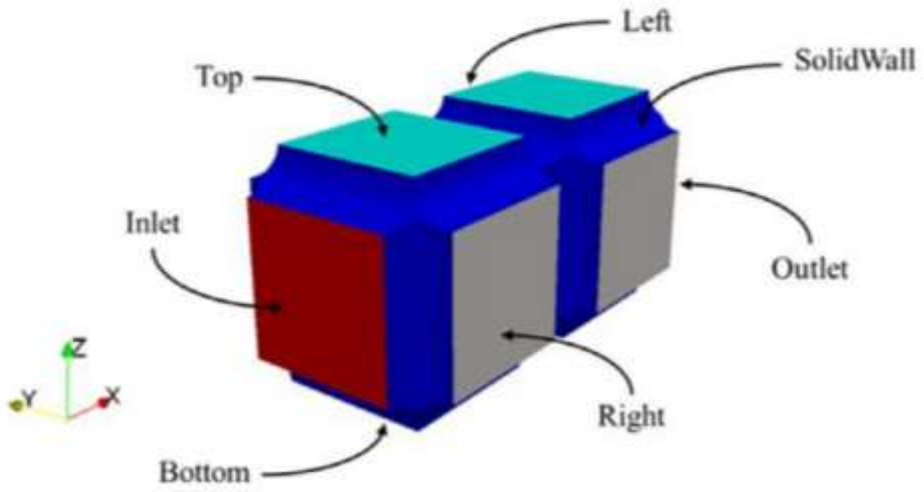
Hydrodynamically and thermally developed flow

- OpenFOAM 6
- Steady, Laminar Flow
- Water at 32 °C ($Pr = 5.2$)



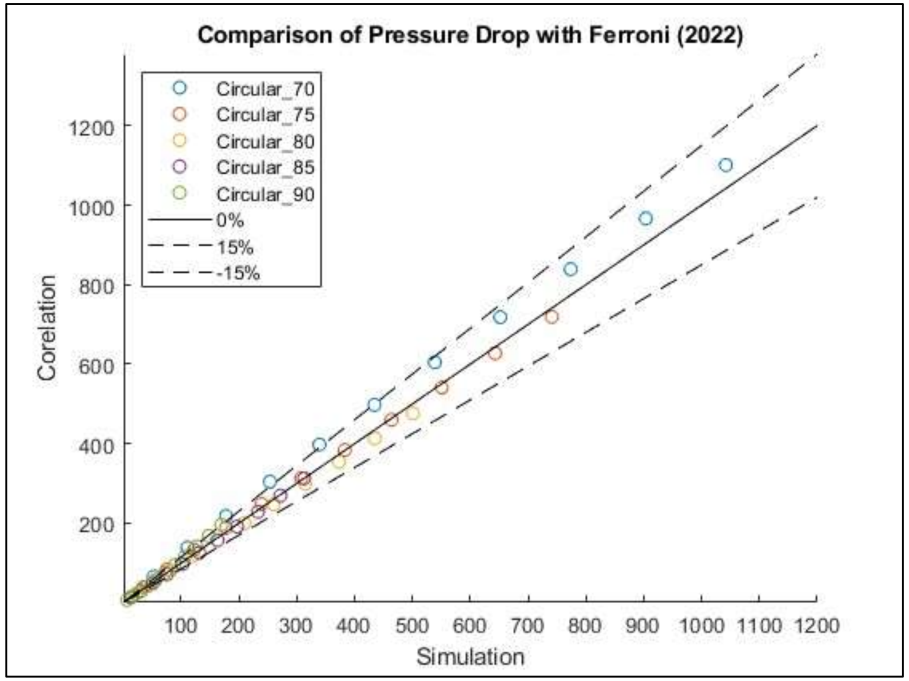
Boundary conditions

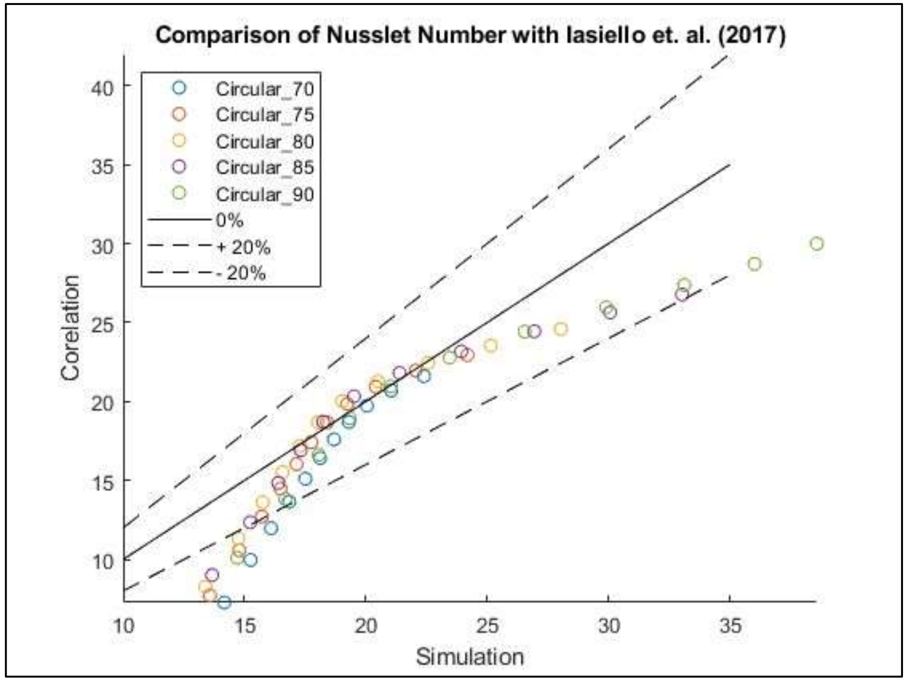
- SolidWall: $\frac{\partial p}{\partial n} = 0;\ \boldsymbol{u} = 0;\ T = 313.15\ \mathrm{K}$
- Top and Bottom: Cyclic
- Right and Left: Cyclic
- Inlet and Outlet: $p_{\mathrm{In}} = p_{\mathrm{Out}} + \Delta p$ [1]; $u_{\mathrm{In}} = u_{\mathrm{Out}}$; $T_{\mathrm{In}} = (T_{\mathrm{Out}} - T_{\mathrm{SW}}) \cdot C + T_{\mathrm{SW}}$ [2]



[1] Martinez et al., International Journal of Thermal Sciences 92 (2015)
[2] Beale, Spalding, Transactions of the CSME 22 (1998)

Validation





MAPE = 5.97 %

MAPE = 12.12%

Hence, the solver is validated ✓

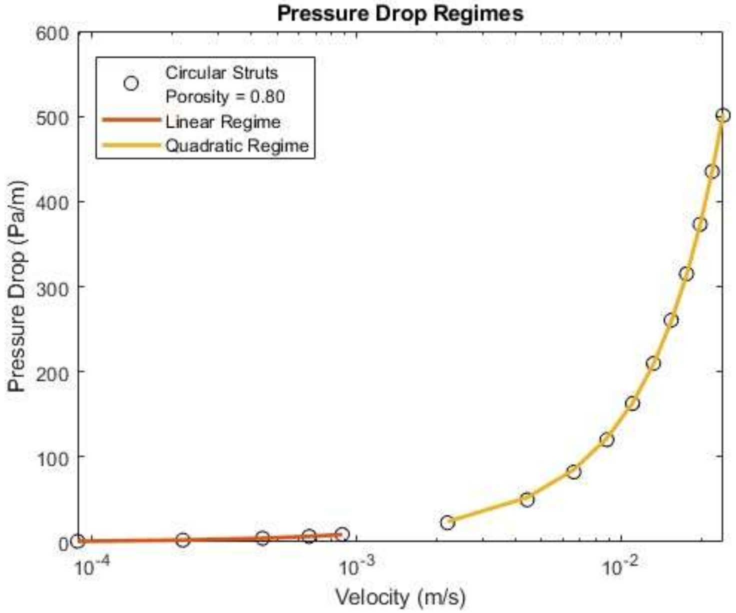
[1] Ferroni et al., ACS Engineering Au 2 (2022)
[2] Iasiello et al, International Journal of Thermal Sciences 111 (2017)

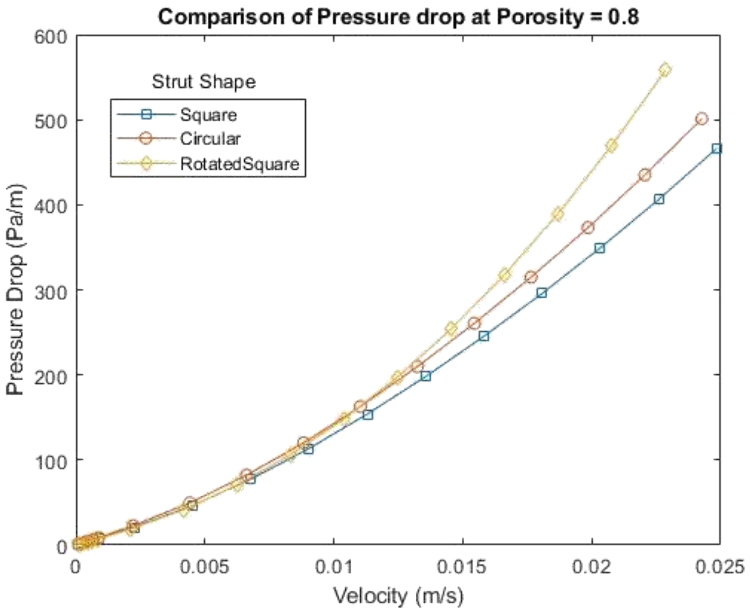
Pressure Drop

Pressure Drop Regimes

- Two distinct regimes - Linear (Darcy) and Quadratic (Forchheimer)

1) $\frac{\Delta P}{L} = \mu \cdot \frac{v}{\kappa}$ 2) $\frac{\Delta P}{L} = \mu \cdot \frac{v}{\kappa} + \beta \cdot \rho \cdot v^2$





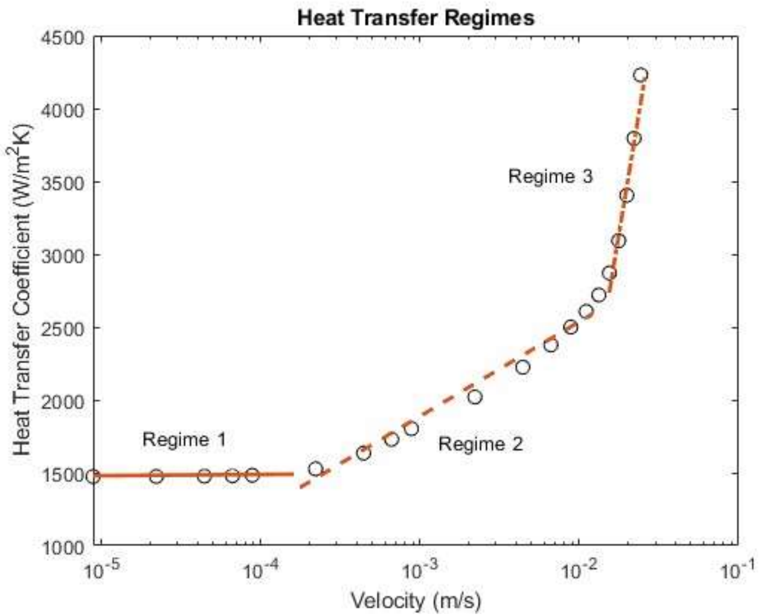
Comparison of Strut Shapes

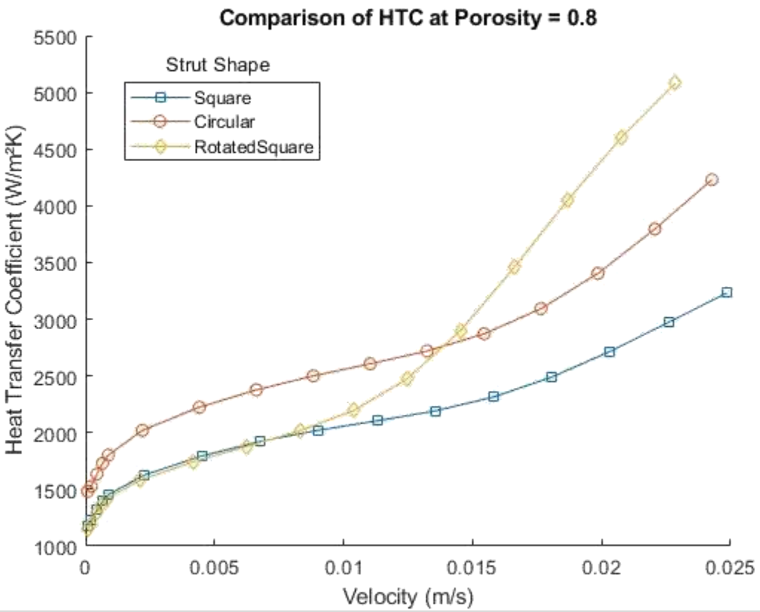
- Pressure drop for Rotated Square > Circular > Square strut shape for all investigated porosities
- Same trend observed for all strut shapes

Convective Heat Transfer

Heat Transfer Regimes

- Three regimes observed: Constant HTC at low velocities, velocity dependent HTC with different slopes in Regime 2 and 3
- Significant change of slope in Regime 3 is a characteristic of the Kelvin cell, not observed in all unit cells





Comparison of Strut Shapes

- HTC for Rotated Square > Circular > Square strut shape for all investigated porosities
- Trend in Regime 1 and 2 is independent of strut shape but Regime 3 is heavily influenced by the strut geometry

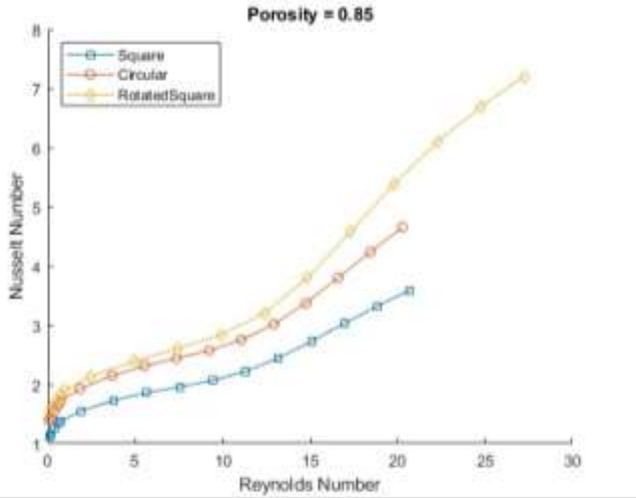
Institute of Thermal Process Engineering
Heat and Mass Transfer

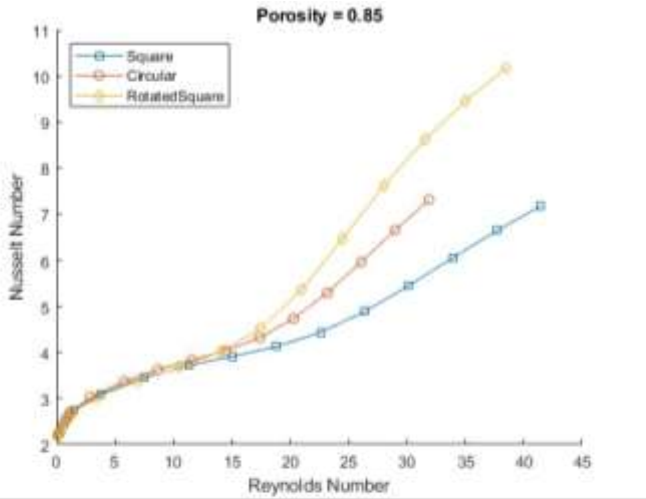
Non Dimensional Analysis

Depending on the characteristic length scale, $\boldsymbol{Nu} = \frac{\boldsymbol{h \cdot L_{char}}}{\boldsymbol{\lambda}}$

$L_{char} = d_s$

L_{char} = Strut semi perimeter





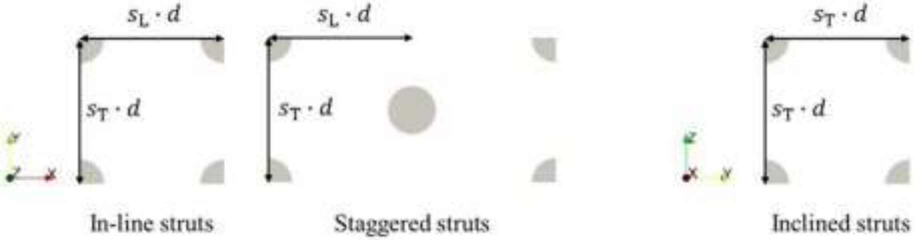
- Nusselt number for Rotated Square > Circular > Square strut shape
- In Regime 1 and 2, the curves follow the same trend, but in Regime 3 the slope is strut shape dependent following the same order as above

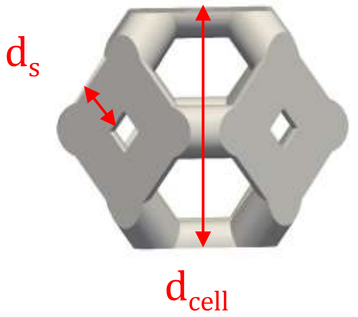
- Nu vs Re characteristics become strut shape independent in Regime 1 and 2
- The transition to regime 3 occurs at the same Re, but again strut shape has an influence on this regime

Superposition Approach [1]

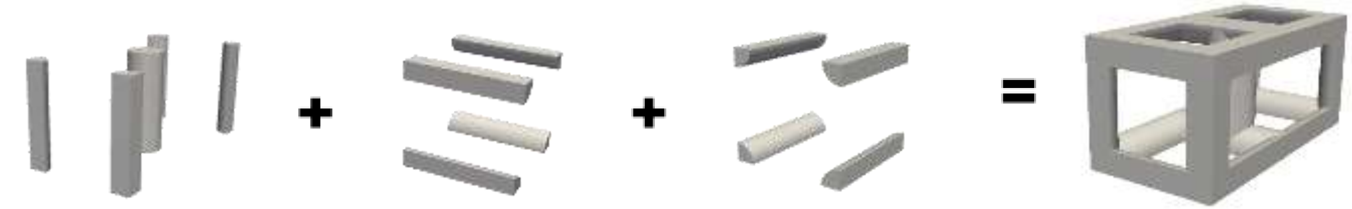
Can the properties of the unit cell be described by a superposition of equivalent strut arrangements?

- Type (F, V, Y), number (N) and pitches (s_T, s_L) of struts need to be determined
- Pitch Definition





$$d_{cell} = s_T d_s$$



Staggered Struts (V) + Inline Struts (F) + Inclined Struts (Y) = Staggered Cubic cell

- Equivalent strut arrangements for the Kelvin Cell

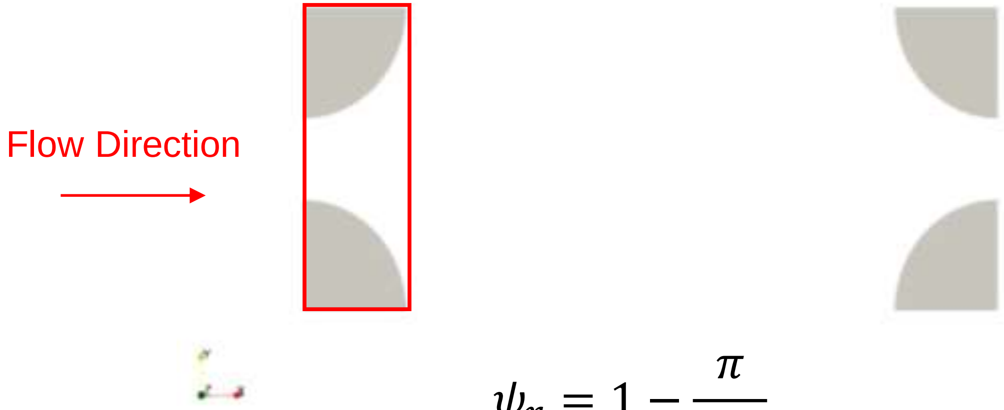
F1			F2			V		
N	$s_{L,strut}$	$s_{T,strut}$	N	$s_{L,strut}$	$s_{T,strut}$	N	$s_{L,strut}$	$s_{T,strut}$
8	s_L	$\sqrt{2}\, s_T/4$	20	$\sqrt{2}\, s_L/2$	s_T	20	$s_L/2$	$\sqrt{2}\, s_L/2$

[1] Dissertation K. Dubil (2023)

Superposition Approach: Hagen Number

- **Hagen number:**

$$Hg = \frac{\frac{\Delta p}{L} \cdot L_{char}^{3} \cdot \rho}{\mu^2}\ ,\ \mathrm{L_{char}} = \begin{cases} \pi d_s/2, & Circular \\ 2\mathrm{d}_s, & Square\ and\ Rotated\ Square \end{cases}$$



- **Superposition:**

$$Hg = \sum_{i=1}^{N} Hg_i \cdot \varphi_i\ ,\ \varphi_i = \frac{N_i}{N} \cdot \frac{S_V}{S_{V,i}}$$

$$\psi_r = 1 - \frac{\pi}{4 s_T}$$

- **Strut Correlations:**

Inlet Porosity : $\psi_{\mathrm{in}} = 1 - \frac{\sqrt{2}}{s_T}$ for the Kelvin Cell

$$Hg_i = \begin{cases} \mathrm{B} \cdot \mathrm{Re}_{in}, & Regime\ 1 \\ \mathrm{B} \cdot Re_{in}^{m}, & Regime\ 2\ and\ 3 \end{cases}$$ where $Re_{in} = \frac{\rho v_0 L_{char}}{\mu \psi_{in}}$

$$Re_{strut} = \frac{\rho v_0 L_{char}}{\mu \psi_r}$$

$$\psi_{in} = 1 - \frac{1}{s_T}$$

- Using ψ_{in} instead of ψ_r for developing the correlations gives better results

Superposition Approach: Nusselt Number

- **Nusselt number:**

$$Nu = \frac{h \cdot L_{char}}{\lambda}, \mathrm{L_{char}} = \begin{cases} \pi d_s/2, & Circular \\ 2\mathrm{d_s}, & Square\ and\ Rotated\ Square \end{cases}$$

- **Superposition:**

$$\mathrm{Nu} = \sum_{i=1}^{N} Nu_i \cdot \frac{A_i}{A}, \quad A_i = N_i \cdot A_{strut} \cdot \phi_{node} \cdot \phi_{proj}$$

$$\phi_{node} = 0.839 \cdot \psi - 0.07 : \text{Reduced strut surface area}$$

Stagnation Zones

$$\phi_{proj} = 1\ for\ F\ and\ V\ struts, \frac{2}{\pi}\ for\ Y\ struts$$

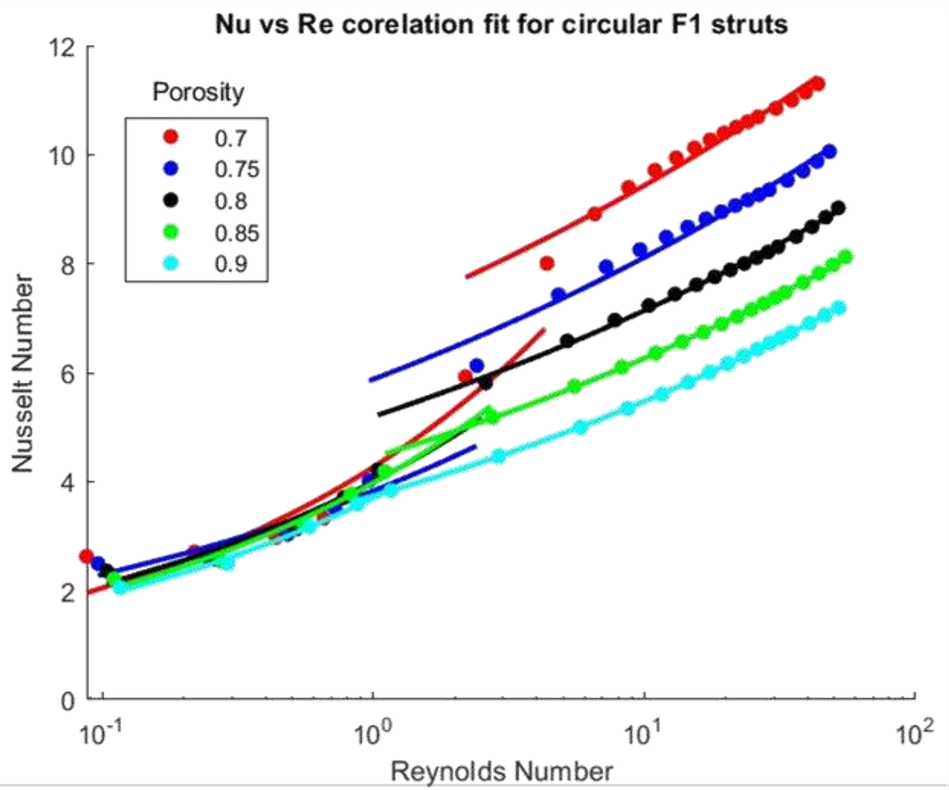
- **Strut Correlations:**

$$Nu_i = \begin{cases} A, & Regime\ 1 \\ A \cdot Re^n, & Regime\ 2\ and\ 3 \end{cases}, \text{ where } Re = \frac{\rho v L_{char}}{\mu}$$

$$Re_{strut} = \frac{\rho v_0 L_{char}}{\mu \psi_r}$$

- **Regime Boundaries:**

$$Re_c = \begin{cases} 7 - 6.6 \cdot \psi, & Regime\ 1-2 \\ 24 - 22 \cdot \psi, & Regime\ 2-3 \end{cases}$$



Results: Hagen Number

- Results using $Re_{in} = \frac{\rho v_0 L_{char}}{\mu \psi_{in}}$

Strut Shape	MAPE	APE < 40%
Circular	54.841	34.615
Square	40.53	54.167
Rotated Square	61.446	25

- Results using $Re = \frac{\rho v_0 L_{char}}{\mu \psi}$

Strut Shape	MAPE	APE < 40 %
Circular	37.688	52.564
Square	32.531	63.542
Rotated Square	29.66	66.25

ψ_{in} = 0.725

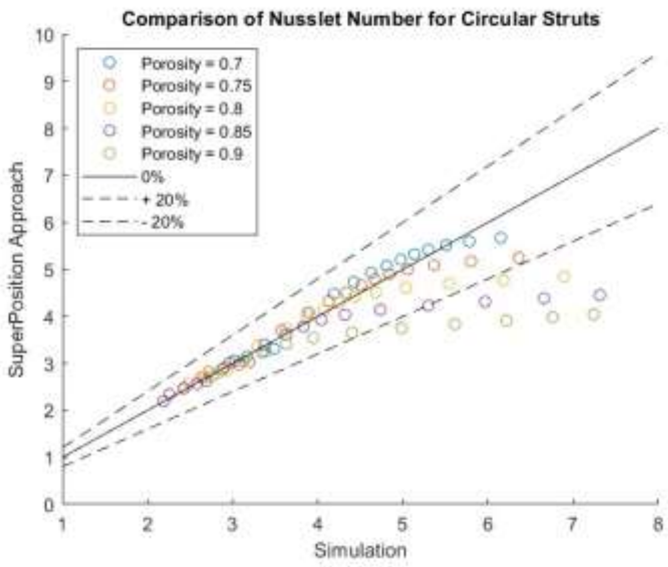
ψ_{in} = 0.758

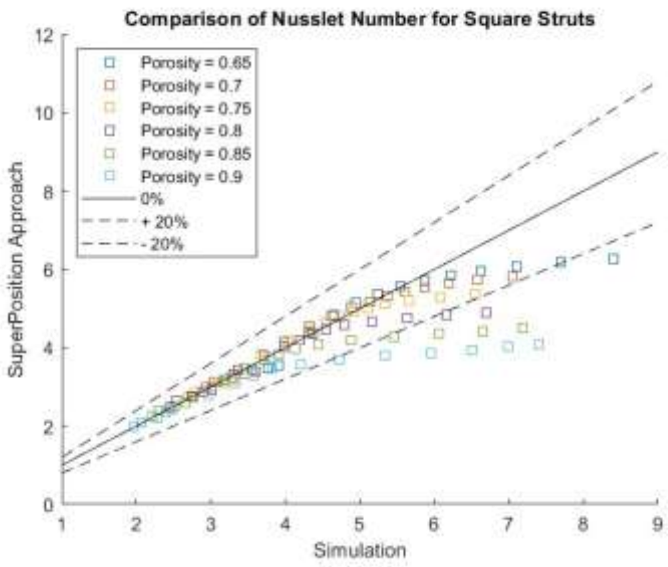
ψ_{in} = 0.658

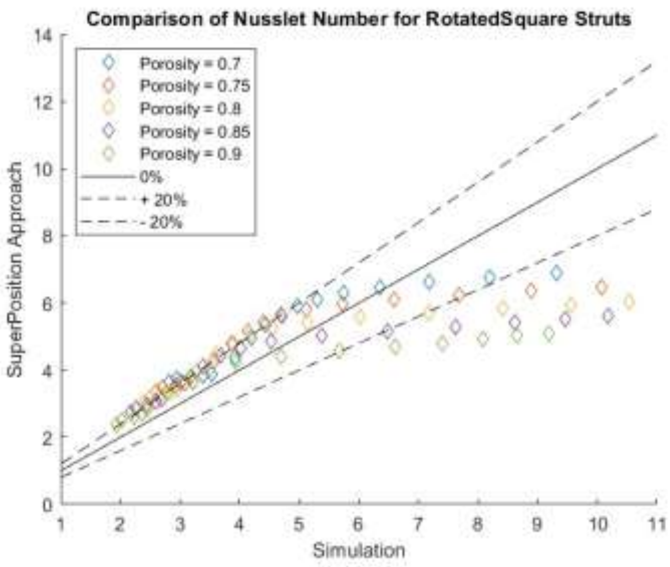
Inlet porosities for ψ= 0.8

- Using Re_{in} in the correlations gives overpredictions
- Higher errors observed in Regime 1
- Errors increase with porosity of the unit cell

Results: Nusselt Number







Strut Shape	MAPE Nu	APE % < 20
Circular	7.9632	85.897
Square	8.1762	86.456
Rotated Square	21.281	47.5

- Higher error at higher Re, in Regime 3
- ϕ_{node} can be modelled as a function of Re to improve predictions in this regime

Remarks

Modifications to the superposition approach specific to the Kelvin cell

Used in this study | Future work

Strut Porosity

- For Hg_i, using inlet porosity for struts as it is more relevant to the pressure drop
- For Nu_i, using the strut row porosity which is related to the strut surface area which directly affects the heat transfer

Regime Boundaries

- The regime boundaries used are a good fit considering different unit cells, only for circular struts
- May not be appropriate for the Kelvin cell and can be dependent on the strut shape

Inlet Reynolds Number

- Replacing Re_{in} by Re reduced the overprediction in results of the Hagen number
- At any cell porosity, the cell inlet porosity is lower which leads to a high inlet Reynolds number

Node Factor

- Nu underpredicted in Regime 3 because of low values of ϕ_{node}
- At higher velocities, the stagnation effect induced by the nodes decreases with velocity and hence ϕ_{node} should increase as a function of Re

THANK YOU