VOF study of gas-liquid multiphase flow in structured separation columns packing

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Introduction
Research motivation
Provide usable tools for separation columns modeling

Importance
- Chemical industry creates mixtures but sells "pure species" (e.g. oil)
- 2014, 3% of energy consumption of the USA was due to the separation columns

Challenges
- Multiphase flow $\rightarrow$ non-steady process
- Complex geometry
- Simultaneous heat and mass transfer
Mellapak type structured packing
Corrugated, perforated sheet of steel equipped with texture
Mass and momentum balance, $N$ phases

$$\rho_i \frac{\partial}{\partial t} (\mathbf{U}_i) + \nabla \cdot (\rho_i \mathbf{U}_i \otimes \mathbf{U}_i) = \nabla \cdot \mathbf{T} + F_i, \quad i = 1, \ldots, N$$

$$\rho_i = \rho(c_i, T_i), \quad \nabla \cdot (\mathbf{U}_i) = S^\rho_i = \sum_{j=1}^{M} \hat{R}^c_{i,j}$$

Mass transfer, $M$ species

$$\frac{\partial}{\partial t} c_{i,j} + \nabla \cdot (\mathbf{U}_i c_{i,j}) = \nabla \cdot (\Gamma^c_{i,j} \nabla c_{i,j}) + S^c_{i,j}, \quad j = 1, \ldots, M$$

Heat transfer, $N$ phases

$$\frac{\partial}{\partial t} T_i + \nabla \cdot (\mathbf{U}_i T_i) = \nabla \cdot (\Gamma^T_i \nabla T_i) + S^T_i, \quad i = 1, \ldots, N$$
Possible simplifications I

Approach the problem from two different sides

- **keep geometry, simplify flow**
- **simplify geometry, keep flow**

\[ U_Y \text{, [m s}^{-1}], \quad \tilde{U}_n \text{, [m}^{-2} s^{-1} \]
Possible simplifications II
Simulate different scales and share informations

Macro scale

Meso scale

Micro scale

Column
[Sulzer Chemtech]

Structured packing
[Sulzer Chemtech]

Inclined plate
[Hoffman 2007]
Project goal
Construct meso scale CFD model of liquid flow in Mellapak type packing

Top $y-z$ slice

Bottom $y-z$ slice

$t = 1.440 \ [s]$

$x-y$ and $x-z$ slices

$||U|| \ [m \cdot s^{-1}]$

$\alpha_L \ [-]\ 0.0 \ 0.25 \ 0.50 \ 0.75 \ 1.0$

VOF study of gas-liquid multiphase flow in structured separation columns packing
Used models
Single phase steady-state incompressible flows
RANS + SST $k - \omega \Rightarrow \text{simpleFoam}$

### Navier-Stokes equations

\[
\begin{align*}
\mathbf{U}_t + \nabla \cdot (\mathbf{U} \otimes \mathbf{U}) - \nabla \cdot \mathbf{T} &= -\nabla \tilde{p} + \tilde{f} \\
\nabla \cdot \mathbf{U} &= 0
\end{align*}
\]

### SST $k - \omega$ model

\[
\begin{align*}
k_t + \mathbf{U} \cdot \nabla k &= \tilde{P}_k + \nabla \cdot [(\nu + \nu_t \sigma_k) \nabla k] - \beta^* k \omega \\

\omega_t + \mathbf{U} \cdot \nabla \omega &= \tilde{P}_\omega + \nabla \cdot [(\nu + \nu_t \sigma_\omega,1) \nabla \omega] \\
&\quad \cdots + \alpha S^2 - \beta \omega^2 + 2(1-F_1)\sigma_\omega,2 \frac{1}{\omega} \nabla k \cdot \nabla \omega
\end{align*}
\]

### BC

\[
\begin{align*}
\mathbf{U} &= G(\mathbf{U}) \\
\tilde{p} &= H(p) \\
k &= K(k) \\
\omega &= L(\omega) \\
on \partial \Omega^h
\end{align*}
\]

### IG

\[
\mathbf{U}_0, \tilde{p}_0, k_0, \omega_0, \nu_0 \quad \text{in } \Omega^h
\]
Momentum and continuity equations

\[
\partial_t (\rho \mathbf{U}) + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) - \nabla \cdot (\mu \nabla \mathbf{U}) = -\nabla p_d - \mathbf{g} \cdot \mathbf{h} \nabla \rho + \mathbf{F}_s
\]

\[
\nabla \cdot \mathbf{U} = 0,
\]

Advection equation for tracked phase volume fraction

\[
\partial_t \alpha + \nabla \cdot (\mathbf{U} \alpha) + \nabla \cdot (\mathbf{U}_r \alpha (1 - \alpha)) = 0,
\]

Notations

$\mathbf{U}[\text{m s}^{-1}]$ ................. bulk velocity

$\mathbf{U}_r[\text{m s}^{-1}]$ ................. compression velocity

$\mu[\text{Pa s}]$ ....................... dynamic viscosity

$\rho[\text{kg m}^{-3}]$ ...................... density

$\gamma[\text{N m}^{-1}]$ ...................... surface tension

$g[\text{m s}^{-2}]$ ...................... gravitational acceleration

$h[\text{m}]$ ...................... reference position vector

$\alpha[-]$ ...................... tracked phase volume fraction
Averaged fluid properties

\[
\rho = \alpha \rho_A + (1 - \alpha) \rho_B, \quad \mu = \alpha \mu_A + (1 - \alpha) \mu_B,
\]
\[
\alpha = \begin{cases} 
1, & \text{cell contains only phase } A \\
0, & \text{cell contains only phase } B \\
\in (0, 1), & \text{cell contains gas-liquid interface}.
\end{cases}
\]

Modeling of the surface forces

\[
F_s = \gamma \n \cdot \kappa(x), \quad \n = \frac{\nabla \alpha}{||\nabla \alpha||}, \quad \kappa(x) = \nabla \cdot \n.
\]

Dynamic contact angle model

\[
n_{wall} = n_w \cos \theta + t_w \sin \theta, \quad \theta = \theta_0 + (\theta_A - \theta_R) \tanh \left( \frac{u_w}{u_\theta} \right).
\]
Preparatory steps
Validation of wetting
Microscale simulations of wetting of inclined plate

\[ \frac{a_s}{a_T} = \frac{a_w}{a_T} \text{[1]} \]

\[ \text{We} = \text{inertia/capillarity} = \frac{\rho U^2 L}{\gamma} \text{[1]} \]

- Cooke et al. (sim)
- HoffMann et al. (sim)
- Iso et al. (sim)
- HoffMann et al. (exp)
- Iso et al. (exp)

We observed the following:

- Drops
- 3 thin rivulets
- Unstable flows
- 1 rivulet and progressing film
- Modified liquid properties

1 rivulet and progressing film
3 thin rivulets
Unstable flows
Modified liquid properties
Drops
Cooke et al. (sim)
HoffMann et al. (sim)
Iso et al. (sim)
HoffMann et al. (exp)
Iso et al. (exp)
Validation of wetting
Microscale simulations of wetting of inclined plate

We \[ a = \frac{a_W}{a_T} \] 

- drops
- 3 thin rivulets
- unstable flow
- 1 rivulet and progressing film

- no texture
- transversal texture
- longitudinal texture
- pyramidal texture

\[ q_s = \frac{a_s}{a_T} \]
Example: $B = \frac{Q_L}{\text{Area(Geometry crosssection)}} = 40 \text{ [m h}^{-1}], \ d_{\text{perf}} = 3 \text{ [mm]}$
Example: $B = 80 \text{[m h}^{-1}]$, $d_{\text{perf}} = 3 \text{[mm]}$, different hole positions
Example: $B = 40 \text{ [m h}^{-1}]$, $d_{\text{perf}} = 5 \text{ [mm]}$
Example: $B = 40 \text{[m h}^{-1}]$, $d_{\text{perf}} = 7 \text{[mm]}$
Geometry generation
Python script based on Blender software

**Step 1:** Create base packing element
Step 2: Construct one corrugate sheet
Step 3: Prepare all the needed sheet
Step 4: Cut out the desired packing shape
Geometry generation
Python script based on Blender software

Step 4: Cut out the desired packing shape
**Step 5:** Perforate the packing
Step 6: Finish the packed bed generation
**Mesh:** Unstructured, hex dominated, \( \text{nCells} \approx 10^6 - 10^7 / \text{packing element} \)
**Testing:** What can be actually measured

**Pressure loss**

\[ \Delta p_h := \frac{p_{\text{above}} - p_{\text{bellow}}}{N_{pk}H_{pk}} \]

**Notations**

- \( N_{pk} [-] \) ............ number of packing elements
- \( H_{pk} [m] \) ............... height of packing element
Single-phase testing
Evaluation of packing dry pressure loss [exp. by Haidl et al., UCT Prague]

\[ \Delta p_{h}, \text{[Pa m}^{-1}\text{]} \]

\[ U_i, \text{[m s}^{-1}\text{]} \]

- M250X, He, CFD
- M250X, N\textsubscript{2}, CFD
- M250Y, He, CFD
- M250Y, N\textsubscript{2}, CFD
- M250Y, SF\textsubscript{6}, CFD

\( \text{CFD} \)

\( \text{Exp.} \)

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OFW'17, Exeter, July 24 - July 27, 2017, VOF study of gas-liquid multiphase flow in structured separation columns packing
Single-phase testing
Evaluation of packing dry pressure loss [exp. by Haidl et al., UCT Prague]

\[ \epsilon_A, \text{[Pa m}^{-1}\text{]} \]

\[ U_i, \text{[m s}^{-1}\text{]} \]

\[ \epsilon_R, \% \]

\[ U_i, \text{[m s}^{-1}\text{]} \]
Superficial liquid velocity: \( B = \frac{Q_{\text{liquid}}}{\text{Area(geom. cross sec.)}} = 200 \, [\text{m} \, \text{h}^{-1}] \)
Example: 100 slices in $y - z$ plane through geometry from previous slide

$$\bar{\alpha}_{L}^{y-z}(x_i) = \frac{1}{\eta^{y-z}(x_i)} \int_{\eta^{y-z}(x_i)} \alpha_L \, dS, \quad \eta^{y-z}(x_i) = \{x \in \Omega^h : x = x_i\}$$
Actual simulations
The original geometry is too big for testing simulations.

**Original geometry:** Cylinder $d_{\text{col}} = 100 - 150$ [mm], $h_{\text{col}} = 210$ [mm] $\rightsquigarrow$ too big for testing

Top $y-z$ slice

Bottom $y-z$ slice

$||U||$ [m s$^{-1}$]

$x-y$ and $x-z$ slices

$t = 1.440$ [s]

$\alpha_L$ [−]
**Auxiliary geometry:** Hexahedron $\Delta x \times \Delta y \times \Delta z = 25 \times 150 \times 24 [\text{mm}] \rightsquigarrow$ used for mesh size independence study and testing of the basic flow behavior
Mesh size independence study
How fine mesh do we need or can afford?

Qualitative comparison: \( L_0 \) mesh, \( \approx 180 \cdot 10^3 \) cells \( L_1 \) mesh, \( \approx 350 \cdot 10^3 \) cells

\[
\begin{align*}
\text{Coarse, } L_0 & \\
\text{Diff.} & \\
\text{Fine, } L_1 & \\
\end{align*}
\]
Mesh size independence study
How fine mesh do we need or can afford?

Qualitative comparison: $L_2$ mesh, $\approx 730 \cdot 10^3$ cells $L_3$ mesh, $\approx 1360 \cdot 10^3$ cells

Coarse, $L_2$

Diff.

Fine, $L_3$

$t = 0.200 \text{ [s]}$
Mesh size independence study
How fine mesh do we need or can afford?

\[ \delta_i^{\alpha} = \left\| \alpha^F(t_i) - \tilde{\alpha}^C(t_i) \right\| \]

\[ \bar{\delta}_{\alpha} = \frac{1}{n\text{Times}} \sum_{(i)} \delta_i^{\alpha} \]

Number of cells in mesh

Used core hours

δ_α

δ_α

δ_i^{\alpha}

δ_i^{\alpha}

\[ \begin{array}{c|c|c|c|c}
\text{Number of cells in mesh} & 347910 & 732979 & 1361919 \\
\hline
\text{Used core hours} & 0.00 & 0.02 & 0.04 & 0.06 & 0.08 & 0.10 & 0.12 & 0.14 & 0.16 & 0.18 & 0.20 \\
\hline
\end{array} \]

\[ \begin{array}{c|c|c|c|c}
\text{Used core hours} & 115 & 114 & 827 & 1000 \\
\hline
\end{array} \]
Mesh size independence study
How fine mesh do we need or can afford?

\[ S_\alpha = \{ x \in \Omega^h : \alpha(x) = 0.5 \} \]

\[ V_\alpha = \{ x \in \Omega^h : \alpha(x) \geq 0.5 \} \]
**Superficial liquid velocity:** $B = \frac{Q_{\text{liquid}}}{\text{Area(geom. cross sec.)}} \text{[m h}^{-1}]$
Real life liquid inlet

\[ d_{\text{col}} = 300 \text{ [mm]} \]

\[ d_{\text{col}} = 150 \text{ [mm]} \]

[Mass trasfer lab. at UCT Prague]

OpenFOAM approximation

\[ d_{\text{col}} = 100 \text{ [mm]} \]
Standard liquid inlet
Shower-like device to "evenly" distribute liquid on column top

Advantages

- Corresponds to the actually used inlet

Disadvantages

- Poor liquid distribution
- Simulation of 1 PE ≈ simulation of the topmost PE ⇒ irrelevant during standard operation

Example of liquid distribution
Simulation of ideal liquid distribution
Assume even liquid distribution on the whole packing

Assume perfectly wetted packing here

simulated packing element
Simulation of ideal liquid distribution
Assume even liquid distribution on the whole packing

Advantages

- Improved liquid distribution
- ”Mid-column conditions”

Disadvantages

- Longer simulation times
- Less stable

Example of liquid distribution
Available experimental data
Usage of 3D X-Ray Tomography


Operation:
- Static X-Ray
- Rotating column

Characteristics:
- Packing: MellapakPlus 752.Y
- $d_{\text{col}} = 100\ [\text{mm}]$
- $h_{\text{bed}} = 800\ [\text{mm}]$, 4 pack. el.
- Rotation time/360°: 45 – 180 [s]
**Available experimental data**

**Usage of 3D X-Ray Tomography**


**Operation:**
- Static X-Ray
- Rotating column

**Characteristics:**
- Packing: MellapakPlus 752.Y
- $d_{col} = 100$ [mm]
- $h_{bed} = 800$ [mm], 4 pack. el.
- Rotation time$/360^\circ$: $45 – 180$ [s]
Available experimental data
Usage of 3D X-Ray Tomography

**Experimental data:** Liquid distribution along the column, 500, 600, 700 and 800 [mm] from the column bottom, $B = 23.1 \text{ [m h}^{-1}]$, MP752Y [S. Aferka et al. *Chem. Eng. Sci.*, 2011.]
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**Available experimental data**

**Usage of 3D X-Ray Tomography**

**Experimental data:** Liquid distribution along the column, 500, 600, 700 and 800 [mm] from the column bottom, \( B = 23.1 \, [\text{m} \, \text{h}^{-1}] \), MP752Y [S. Aferka et al. *Chem. Eng. Sci.*, 2011.]
Experimental data: Liquid distribution along the column, 500, 600, 700 and 800 [mm] from the column bottom, $B = 23.1 \text{ [m h}^{-1}\text{]}$, MP752Y [S. Aferka et al. *Chem. Eng. Sci.*, 2011.]
Liquid distribution in packing

Calculate "volume fraction" of liquid along the packing

**Example:** MP250X packing, \( d_{col} = 150 \text{[mm]} \), \( H_{pkg} = 200 \text{[mm]} \), \( B = 10.2 \text{[m h}^{-1}] \), 100 slices along \( x \) coordinate, old inlet

\[
\bar{\alpha}_L^{y-z}(x_i) = \frac{1}{\eta^{y-z}(x_i)} \int_{\eta^{y-z}(x_i)} \alpha_L \, dS, \quad \eta^{y-z}(x_i) = \{ \mathbf{x} \in \Omega^h : x = x_i \}
\]
**Example:** MP250X packing, \(d_{\text{col}} = 150 \text{[mm]}\), \(H_{\text{pkg}} = 200 \text{[mm]}\), \(B = 10.2 \text{[m h}^{-1}]\), 100 slices along \(x\) coordinate, old inlet
Example: MP750Y packing, $d_{col} = 100 \text{[mm]}$, $H_{pkg} = 200 \text{[mm]}$, $B = 23.1 \text{[m h}^{-1}]$, 100 slices along $x$ coordinate

\[
\overline{\alpha}_L^{y-z}(x_i) = \frac{1}{\eta^{y-z}(x_i)} \int_{\eta^{y-z}(x_i)} \alpha_L \, dS, \quad \eta^{y-z}(x_i) = \{ x \in \Omega^h : x = x_i \}
\]
**Example:** MP750Y packing, $d_{col} = 100 \text{[mm]}$, $H_{pkg} = 200 \text{[mm]}$, $B = 23.1 \text{[m h}^{-1}]$, 100 slices along $x$ coordinate.
Liquid distribution in packing

Calculate "volume fraction" of liquid along the packing

**Example:** MP750Y packing, \( d_{col} = 100 \, [\text{mm}] \), \( H_{pkg} = 200 \, [\text{mm}] \), \( B = 23.1 \, [\text{m h}^{-1}] \), 100 slices along \( x \) coordinate
Liquid distribution in packing
Qualitative exploration of liquid distribution

$t = 2.07$ [s]

$\alpha_L$ [-]

1.0

0.75

0.50

0.25

0.0
Conclusions
Conclusions
Multiphase simulation for liquid flow on structured packing

Currently available

- Single phase steady state simulations $\rightarrow$ dry pressure loss estimation
- Multiphase simulations (limited dataset)

Next steps

- Finish the multiphase simulations
- Compare liquid hold up with experimental data
- Calculate wet pressure loss (moderate gas flow rates) and compare it with experimental data
Other research branches
Testing different types of packing

Random packings

Superpak packing

||U|| [m s\(^{-1}\)]

0.50
0.20
0.10
0.050
0.020
0.010
0.0050
0.0020
0.0010

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Acknowledgments

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Special thanks to the Mass Transfer Research Group of the University of Chemistry and Technology in Prague for providing an acces to their experimental equipment as for as for many helpfull consults.
References


Thank you for your attention
Microscale simulations
Mesh size independence study - transversal texture

![Graph showing mesh size independence study](image)

- Number of cells in mesh:
  - 276000 cells
  - 493120 cells
  - 706560 cells
  - 1104000 cells
  - 1725000 cells

- Used core hours:
  - 71
  - 80
  - 73
  - 83
  - 149

- Time [s]:

- Used core hours:
  - 0
  - 50
  - 100
  - 150

- Number of cells in mesh:
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1.0
  - 1.2
  - 1.4
  - 1.6
  - 1.8

δi

δ

α

α
**Wetted to total area ratio:** Flow regimes in dependence on $\text{We}_{l/N}$

(a) $\text{We}_{l/N} = 0.05$
(b) $\text{We}_{l/N} = 0.33$
(c) $\text{We}_{l/N} = 0.73$
(d) $\text{We}_{l/N} = 1.01$
(e) $\text{We}_{l/N} = 1.32$

Single phase model – mesh size determination

Main variable of interest is dry pressure loss, $\Delta p_h$. 

![Graph showing $\Delta p_h$ vs. nCells, runtime, and relative difference vs. refinement level.]

<table>
<thead>
<tr>
<th>nCells, [1]</th>
<th>$\Delta p_h$, [Pa m$^{-1}$]</th>
<th>runtime, [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.31</td>
<td>20.26</td>
</tr>
<tr>
<td>2</td>
<td>5.87</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>8.82</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>13.79</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>31.58</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>41.45</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>50.26</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>refinement level, [1]</th>
<th>rel. difference, [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10.0</td>
</tr>
<tr>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>1</td>
<td>6.0</td>
</tr>
<tr>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
</tr>
<tr>
<td>3.5</td>
<td>0.0</td>
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<tr>
<td>4</td>
<td>0.0</td>
</tr>
<tr>
<td>4.5</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Main variable of interest is dry pressure loss, $\Delta p_h$.

**Mesh sizes:** Mesh with $n_{\text{Cells}} \approx 1 \cdot 10^6$/packing element
Single phase model – mesh size determination
Main variable of interest is dry pressure loss, $\Delta p_h$

**Mesh sizes:** Mesh with \( n_{\text{Cells}} \approx 2.5 \cdot 10^6 / \text{packing element} \)
Mesh sizes: Mesh with $n_{\text{Cells}} \approx 3.8 \cdot 10^6$/packing element
Single phase model – mesh size determination

Main variable of interest is dry pressure loss, $\Delta p_h$.

**Mesh sizes:** Mesh with $n_{\text{Cells}} \approx 5.3 \cdot 10^6$/packing element

$L_3$
Single phase model – mesh size determination
Main variable of interest is dry pressure loss, $\Delta p_h$

**Mesh sizes:** Side view on mesh levels 0 – 3
Result: flow patterns in 1 packing packing element
Single phase model – flow in two packing elements
Flow keeps its structure in most of the packing

**Simulation:** Change of flow at transition between packing elements
Single phase model – mellapak packing mixing properties

Gas mixing in two packing elements

Seed: \( \sigma_1 = \{(x, y, z) \in S : x = -0.22 \text{ m}, y^2 + z^2 \leq 0.025^2 \text{ m}\} \)
Seed: $\sigma_1 = \{(x, y, z) \in S : x = -0.22 \text{ m}, y^2 + z^2 \leq 0.025^2 \text{ m}\}$
Seed: $\sigma_2 = \{(x, y, z) \in S : x = -0.22\text{m}, 0.07^2\text{m} \leq y^2 + z^2 \leq 0.075^2\text{m}\}$
Seed: \( \sigma_2 = \{(x, y, z) \in S : x = -0.22m, 0.07^2m \leq y^2 + z^2 \leq 0.075^2m\} \)
Single phase model – changes in the geometry
Different channel inclination angles and perforation densities
Variable for comparison: Normalized dry pressure loss

\[(\Delta p_h)^i_n := \frac{\Delta p_h^i - \min(i)\Delta p_h}{\max(i)\Delta p_h - \min(i)\Delta p_h} \in \langle 0, 1 \rangle\]
Single phase model – dry pressure loss estimation

Different channel inclination angles

\[ \Delta p_{n} = \frac{\rho_{f} g h}{\left( \frac{u_{0}}{\tan \alpha_{ch}} \right)^{2}} \]

- \( \alpha_{ch} \), [deg]
- \( \Delta p_{n}, [l] \)

- \( N_2, u_0 = 3.05 \text{ m s}^{-1} \)
- \( \text{He}, u_0 = 1.05 \text{ m s}^{-1} \)
- \( \text{SF}_6, u_0 = 1.94 \text{ m s}^{-1} \)
Single phase model – dry pressure loss estimation

Different perforation density

\[ a_{pr}^Y = 2.0 \cdot 10^{-2} \text{ m} \]

\[ a_{pr}^Y = 4.0 \cdot 10^{-2} \text{ m} \]
Single phase model – dry pressure loss estimation

Different perforation density

\[ \Delta p_h \propto Y_{pr}, \{m\} \]

\[ N_2, \text{Re} = 2584 \]
\[ \text{He}, \text{Re} = 128 \]
\[ \text{SF}_6, \text{Re} = 9125 \]
**Ranges of $\Delta p_h$ during the simulations**

<table>
<thead>
<tr>
<th>Case</th>
<th>Varied parameter</th>
<th>min $\Delta p_h$, Pa m$^{-1}$</th>
<th>max $\Delta p_h$, Pa m$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_2$</td>
<td>$\alpha_{ch}$</td>
<td>112.96</td>
<td>439.00</td>
</tr>
<tr>
<td>He</td>
<td>$\alpha_{ch}$</td>
<td>9.00</td>
<td>17.22</td>
</tr>
<tr>
<td>SF$_6$</td>
<td>$\alpha_{ch}$</td>
<td>172.62</td>
<td>824.03</td>
</tr>
<tr>
<td>$N_2$</td>
<td>$a_{pr}^Y$</td>
<td>295.34</td>
<td>310.07</td>
</tr>
<tr>
<td>He</td>
<td>$a_{pr}^Y$</td>
<td>14.19</td>
<td>14.46</td>
</tr>
<tr>
<td>SF$_6$</td>
<td>$a_{pr}^Y$</td>
<td>530.16</td>
<td>543.85</td>
</tr>
</tbody>
</table>

- Channel inclination has substantially larger effect on $\Delta p_h$ than perforation
Theory: Flow perturbation in the perforation vicinity

Wall shear stress on the packing

\[ a_{pr}^Y = 2.7 \times 10^{-2} \text{ m} \]

\[ a_{pr}^Y = 4.0 \times 10^{-2} \text{ m} \]
**Theory:** Flow perturbation in the perforation vicinity

**Reynolds stress around holes**

\[ a_{pr}^y = 2.7 \cdot 10^{-2} \text{ m} \]

\[ a_{pr}^y = 4.0 \cdot 10^{-2} \text{ m} \]