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A novel concept for characterisation of the micro-permeability of fibre bundles based on macro-scale flow experiments

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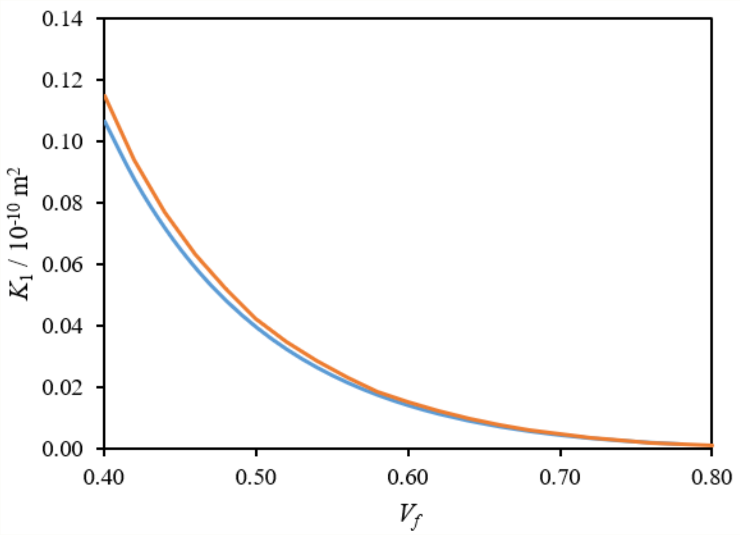
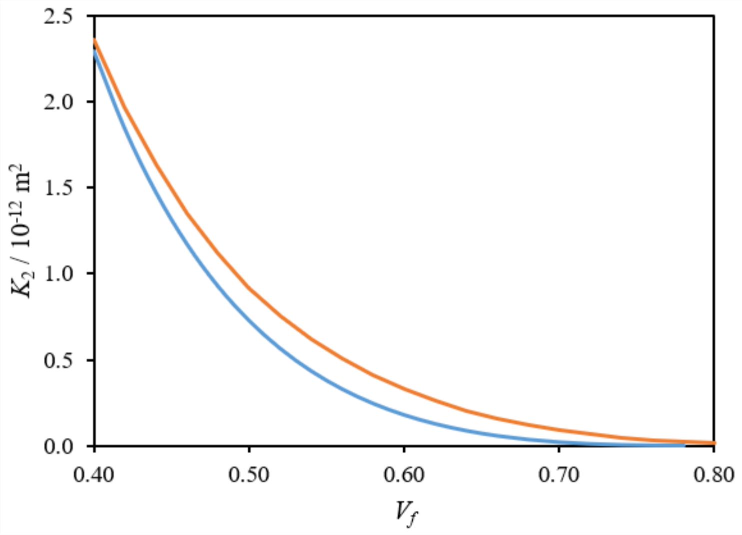
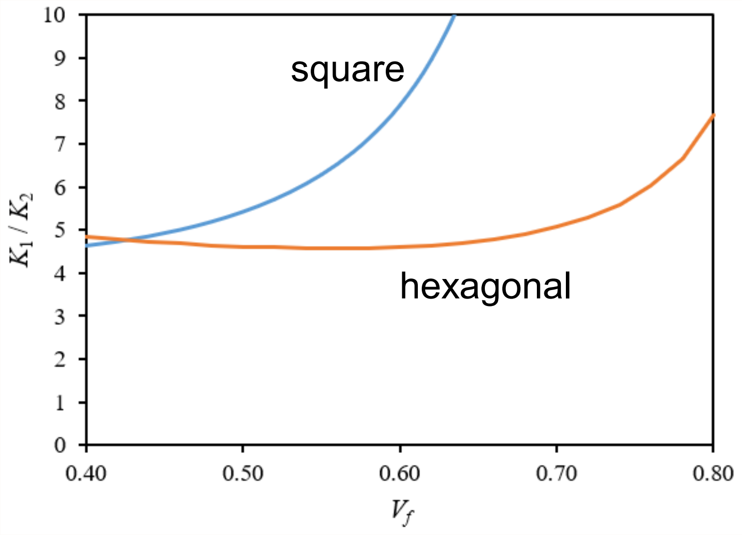
Fibre bundle permeability: Theory

Equations by Gebart

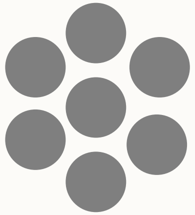


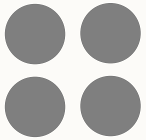




(assumption: filament diameter $15\ \mu m$)

Two idealised configurations

hexagonal  $V_{fmax} = \frac{\pi}{2\sqrt{3}} = 0.907$

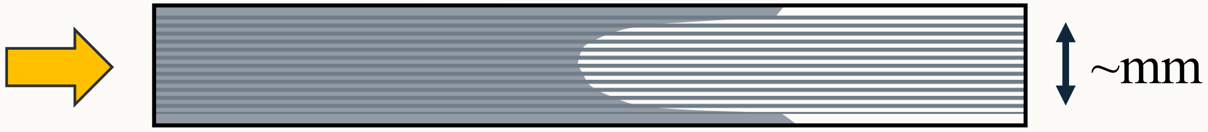
square  $V_{fmax} = \frac{\pi}{4} = 0.786$

Experiments: Literature

Permeability measurement in 1D flow experiments

Problem:

Small bundle width ➡ Edge effects can be significant



Width of racetracking channels impossible to control

Proposed solution:

Embed bundles in sealant to prevent edge flow / racetracking

Effective width and cross-sectional shape unknown

Schell JSU, Siegrist M, Ermanni P. Experimental determination of the transversal and longitudinal fibre bundle permeability. *Appl Compos Mater* 2007; 14(2): 117–128.

Zarandi MAF, Arroyo S, Pillai KM. Longitudinal and trans-verse flows in fiber tows: evaluation of theoretical permeability models through numerical predictions and experimental measurements. *Compos Part A-Appl S* 2019; 119: 73-87.

Experiments: Literature

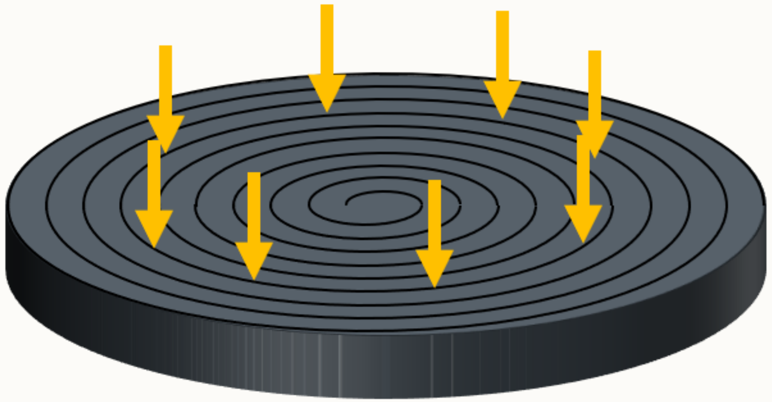
To avoid edge flow

- Roll-up fibre bundle into disk
- Measure permeability of disk

2D radial flow

➡ transverse bundle permeability in *thickness*-direction

Wu X, Li J, Shenoi RA. A new method to determine fiber transverse permeability. *J Compos Mater* 2007; 41(6): 747-756.

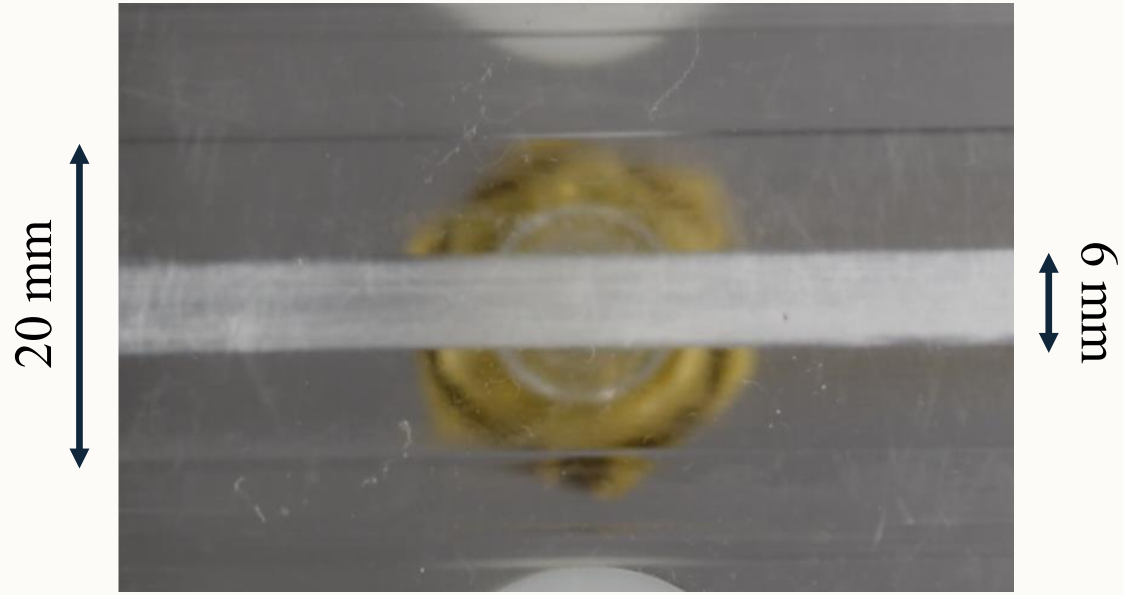


1D flow normal to disk

➡ transverse bundle permeability in *width*-direction

Yuksel O, Caglar B, Broggi G, Michaud V, Akkerman R, Baran I. Saturated transverse permeability of unidirectional rovings for pultrusion: The effect of microstructural evolution through compaction. *Polym Composite* 2024; 45(7): 5935-5952.

Experiments: Micro-injection



Perspex tool, visual flow monitoring

height of channel	h	0.2 mm
width of channel	w	20 mm
inlet diameter	d	1 mm
temperature	T	20 °C
viscosity	η	0.103 Pa×s
pressure	Δp	0.5 bar
fibre density	ρ	2550 kg/m^3
linear density	λ	2400 tex

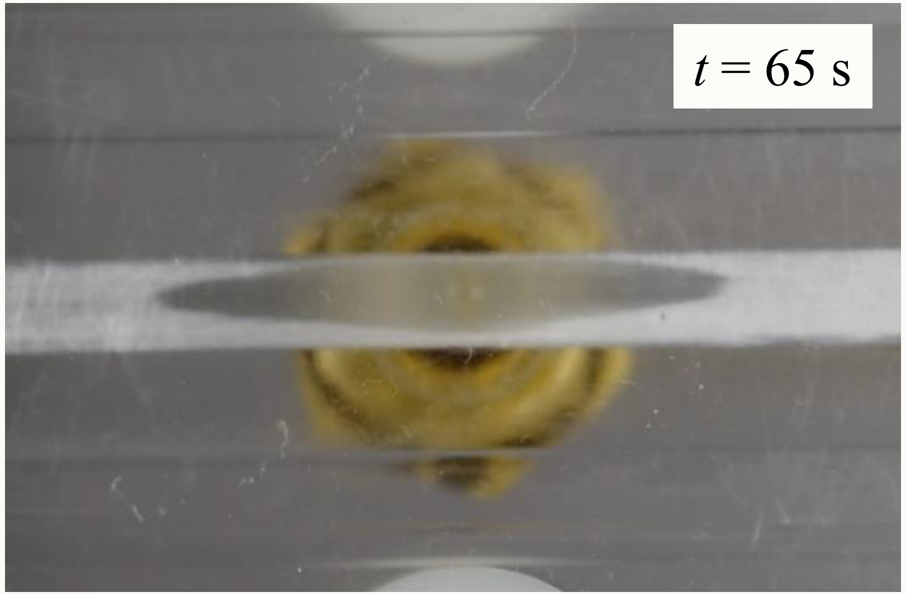
Total cross-sectional area of fibres

$$A_f = \frac{\lambda}{\rho} = \frac{2.4\times10^{-3}\ \text{kg/m}}{2550\,\text{kg/m}^3} = 9.41\times10^{-7}\ \text{m}^2$$

Fibre volume fraction

$$V_f = \frac{A_f}{h\,w_b} \qquad V_f = 0.78$$

Experiments: Micro-injection



5.08 mm

37.15 mm

Principal permeabilities

$K_1 = 3.67\times10^{-12}$ m^2 $\quad$ $K_2 = 6.86\times10^{-14}$ m^2

$K_1/K_2 \approx 54$

2D radial flow

$$k_e = \frac{\Phi \eta R_{01}^2}{4\Delta p t}\left(\left(\frac{R_1}{R_0}\right)^2\left(2\ln\left(\frac{R_1}{R_0}\right)-1\right)+1\right)$$

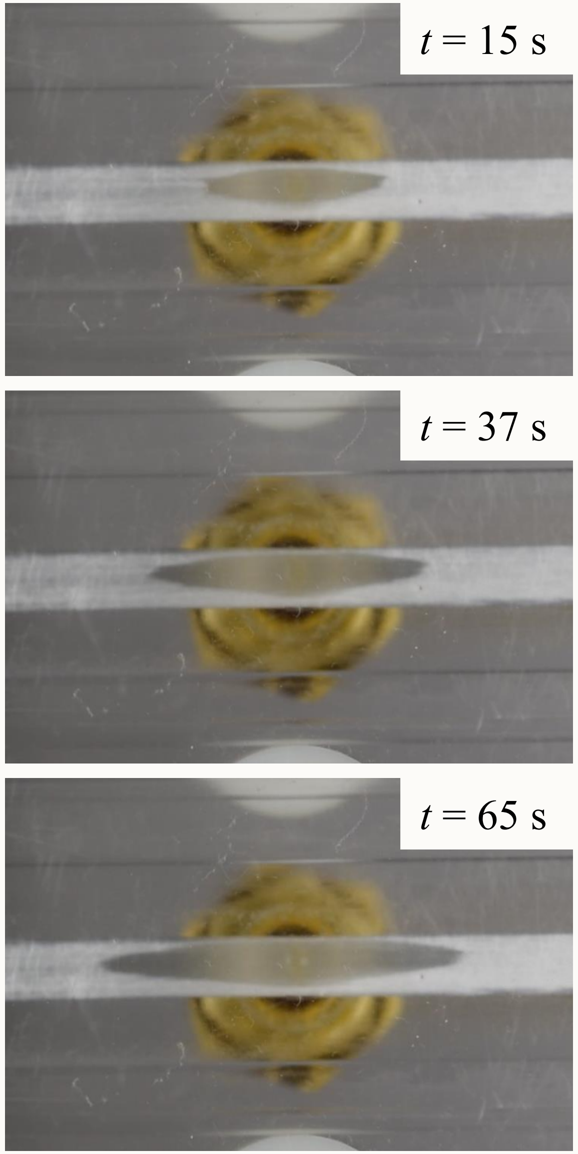
$$R_{01} = \sqrt{\frac{R_2}{R_1}}\frac{d}{2}$$

$$K_1 = k_e\frac{R_1}{R_2} \quad \text{and} \quad K_2 = k_e\frac{R_2}{R_1}$$

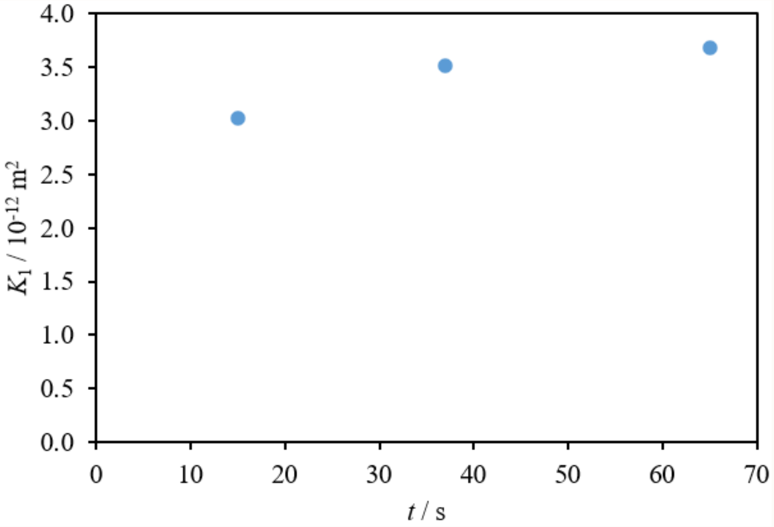
Caveats

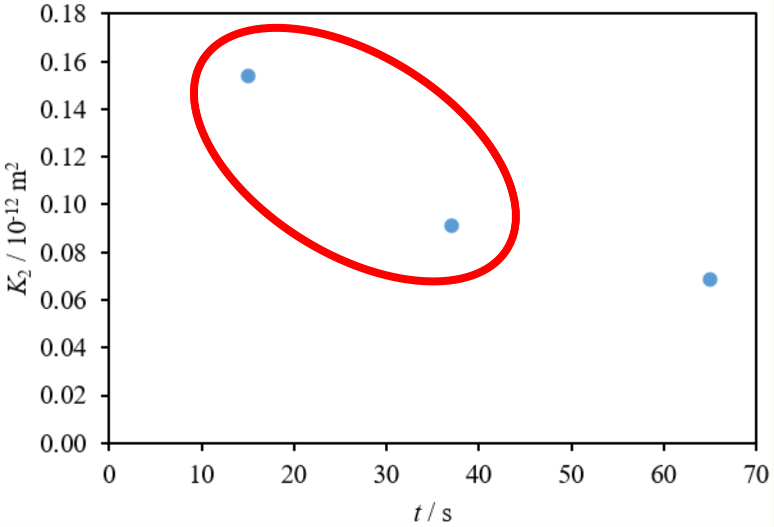
- A hole cannot be stamped into bundle, so strictly speaking not purely 2D flow
- Large ratio K_1/K_2
- Hole diameter is not small compared to flow front ellipse width

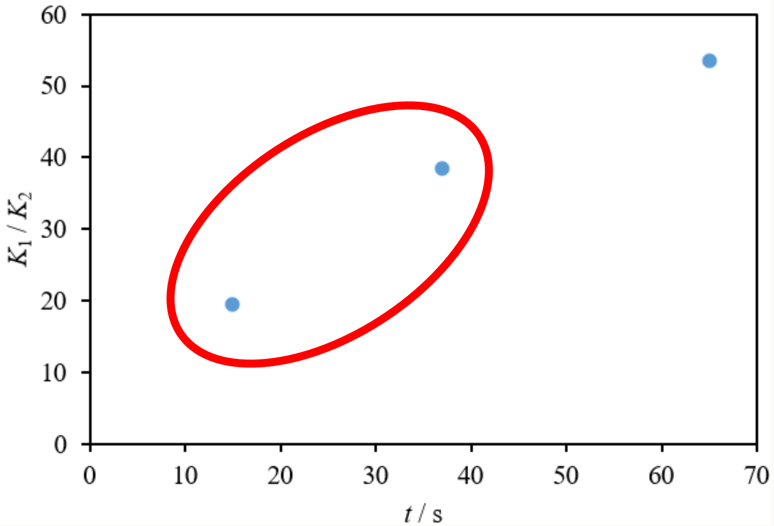
Experiments: Micro-injection



Evaluate flow at different times

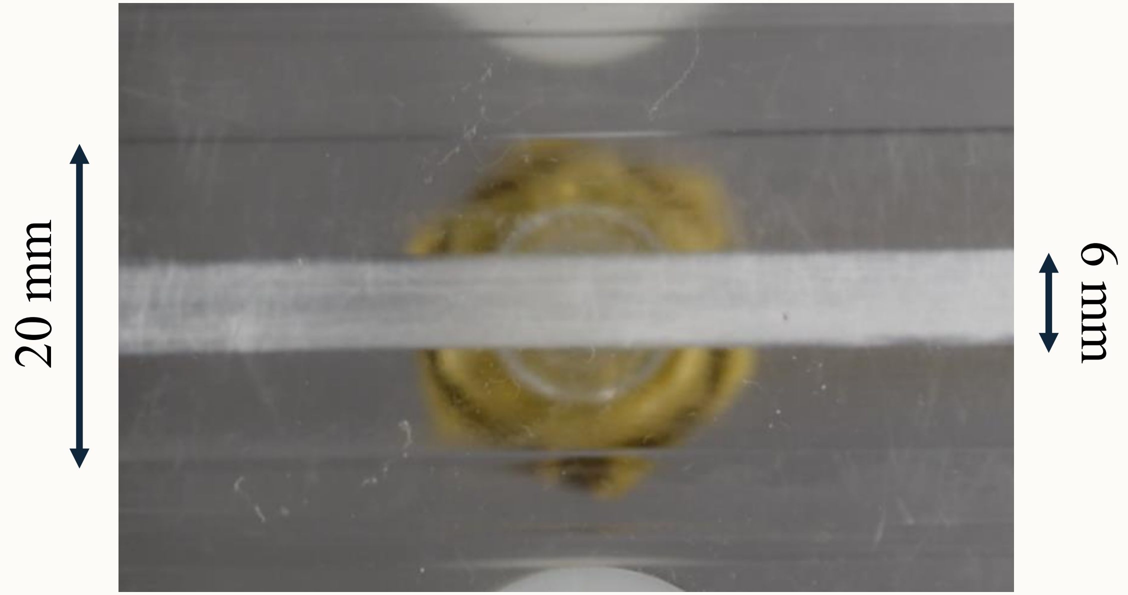






Apparent variation in K_2:
Flow front width too small compared to inlet diameter

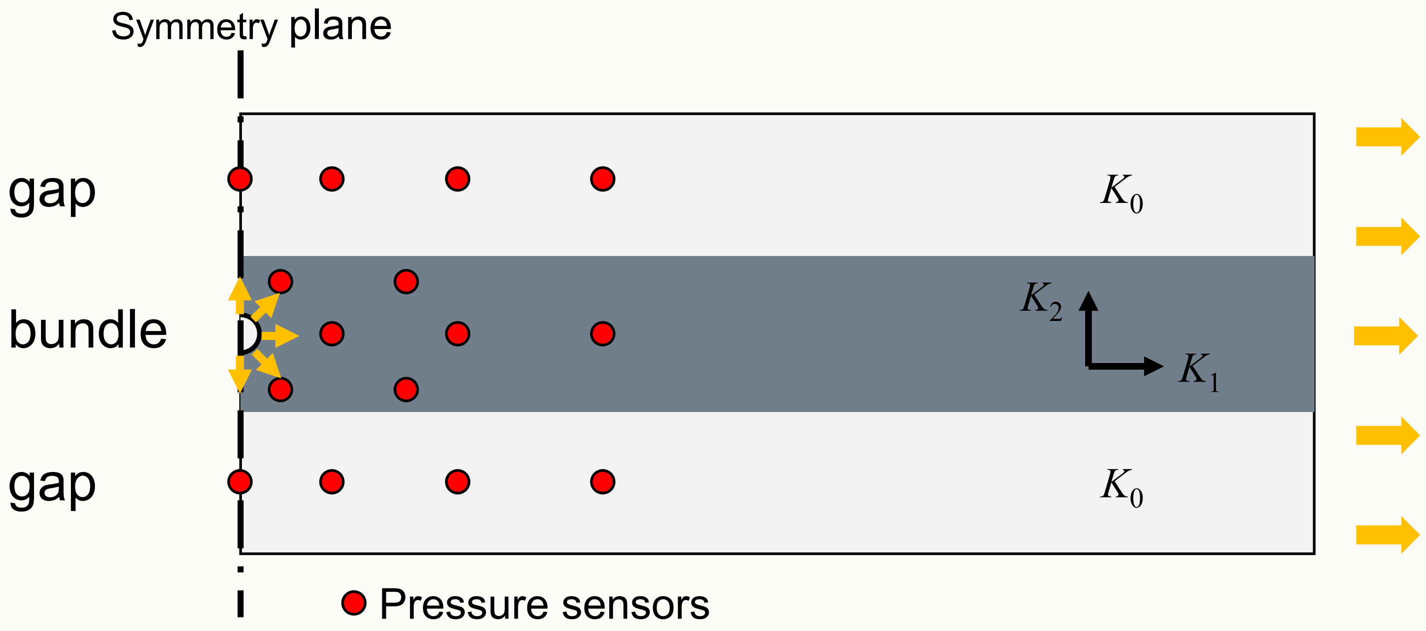
Experiments: New concept

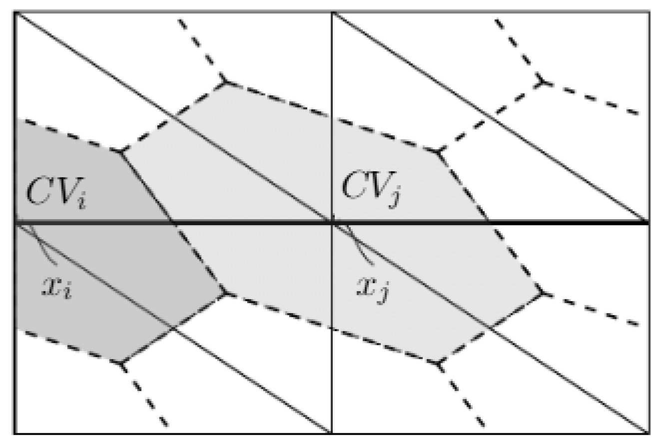


- Same set-up as before
- Consider flow in fibre bundle ***and in gaps on both sides***
- Apply inversion algorithm to find permeabilities of bundle and of gaps
- **Racetracking is part of the solution**

Here:
Use Ensemble Kalman Inversion which aims to minimise the difference between pressure-time curves obtained from an experiment (or virtual experiment) and the ensemble of possible solutions to find approximations for permeability.

Virtual experiment: Set-up





Use MATLAB implementation of CVFEM for simulation

Wells, H., Park, M., Matveev, M., & Tretyakov, M. (2024). RTM-Flow: Control volume FEM solver for 2D moving boundary problems (v2.0). Zenodo. https://doi.org/10.5281/zenodo.12583662

Input data

h	0.2 mm
w	20 mm
d	1 mm
l	100 mm
η	0.1 Pa×s
Δp	0.5 bar
Φ	0.78
K_1	3.65×10^{-12} m^2
K_2	6.84×10^{-14} m^2
K_0	10^{-8} m^2

A sinusoidal variation of ±10 % is applied to K_1 and K_2 (in axial direction).

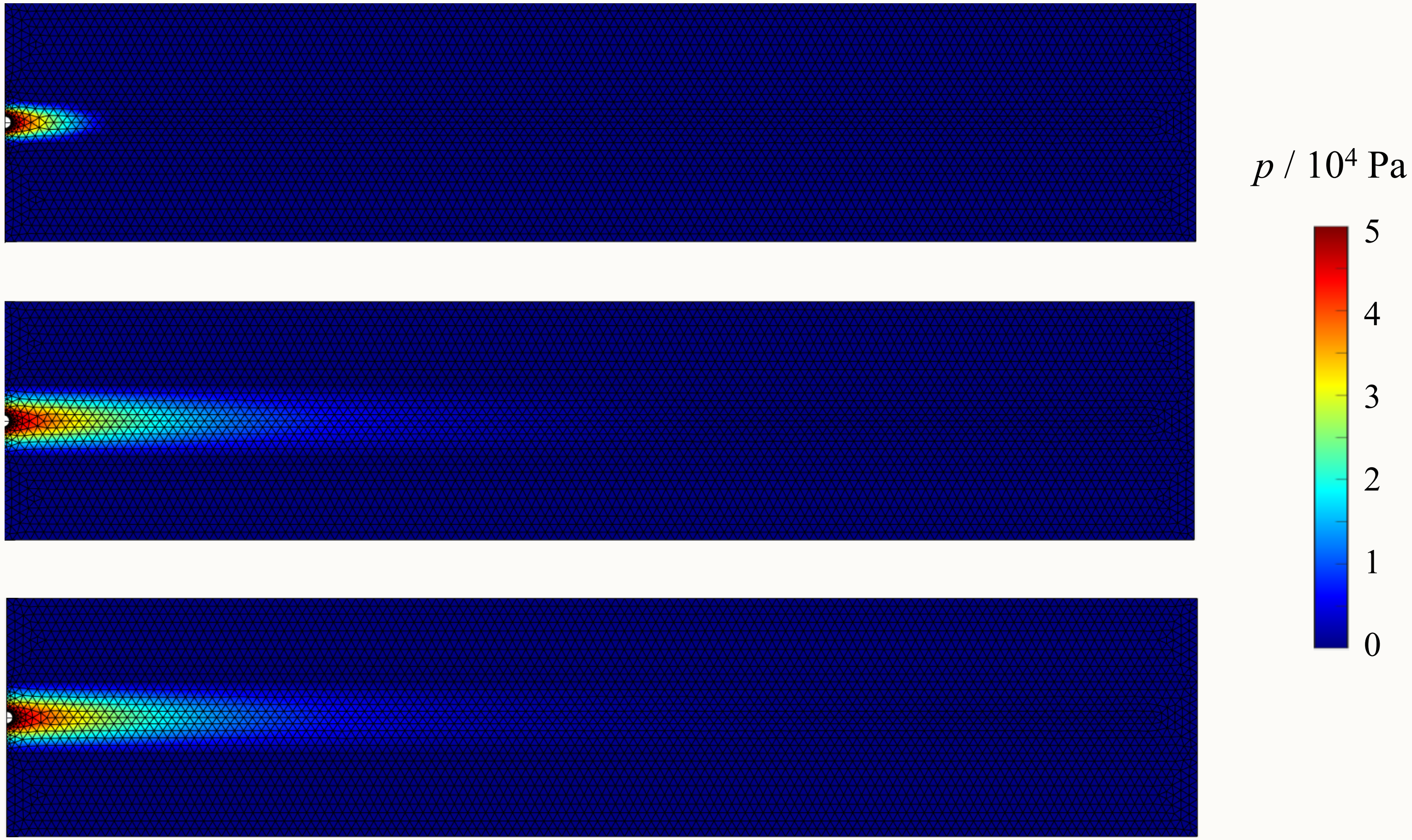
Virtual experiment: Results

Pressure distributions at different times ***during impregnation***

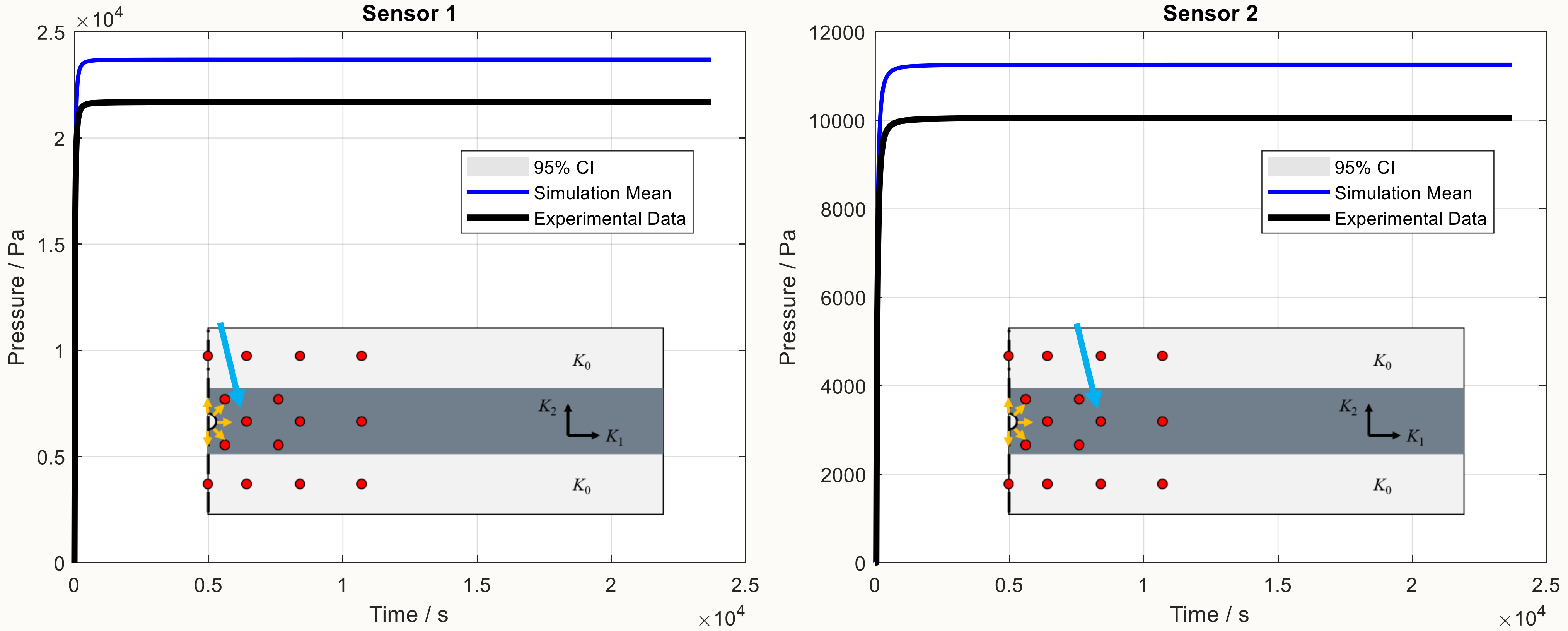
$t = 5$ s

$t = 1193$ s

$t = 20729$ s



Virtual experiment: Results



Inversion on ***full transient data***
(for all sensors)

	input	recovered	difference
K_1 / 10^{-12} m^2	3.65	3.74 ± 0.01	+ 2 %
K_2 / 10^{-14} m^2	6.84	7.06 ± 0.02	+ 3 %
K_0 / 10^{-8} m^2	1.00	2.99 ± 1.07	+ 199 %

Virtual experiment: Results

Flow in fibre bundles:

- Small spaces between filaments
- Relatively small applied pressure gradient

→ Capillary pressure may have significant effect on results in ***physical*** experiments

To avoid effect of capillary effects,
run ***saturated flow experiments*** and
use ***stationary local pressure readings*** for inversion

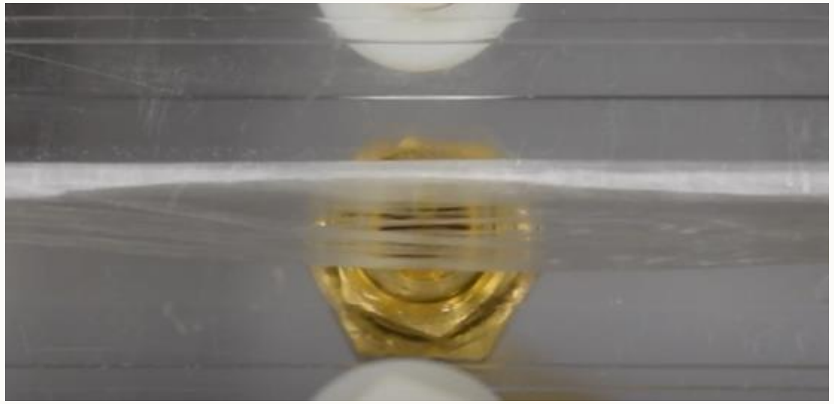
Results of the saturated (virtual) case:

Inversion ***on steady-state pressure values***

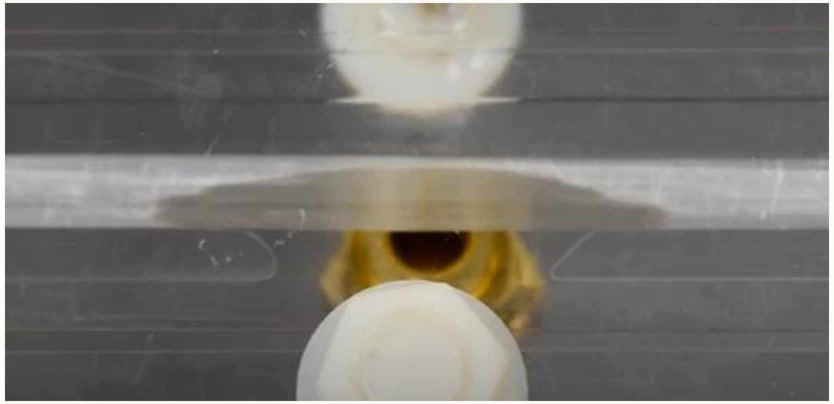
	input	recovered	difference
K_1 / 10^{-12} m^2	3.65	4.35 ± 0.06	+ 19 %
K_2 / 10^{-14} m^2	6.84	7.81 ± 0.10	+ 14 %
K_0 / 10^{-8} m^2	1.00	0.95 ± 0.03	- 5 %

Potential issues

- Bundle splits when injection pressure is too high compared to compaction pressure holding bundle in place
  Cannot be solved

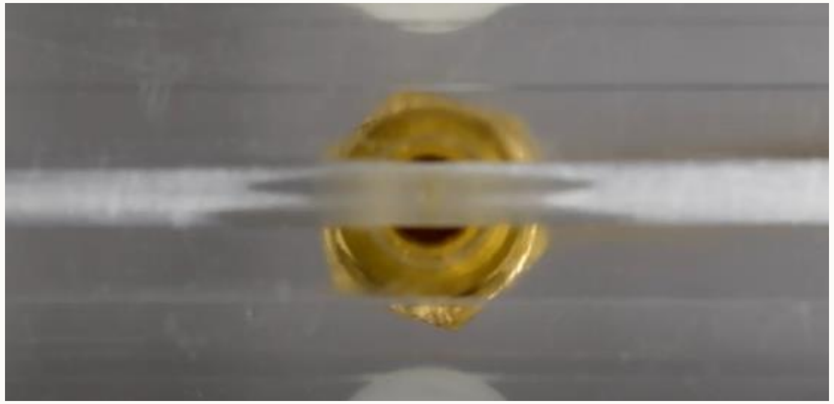


- Bundle not aligned symmetrically on inlet
  Can be solved if geometry is varied



- Non-uniform bundle permeability

  Can be solved but requires additional variables



Conclusions

Different approaches are documented for characterisation of fibre bundle permeabilities. All implement measures to avoid racetracking.

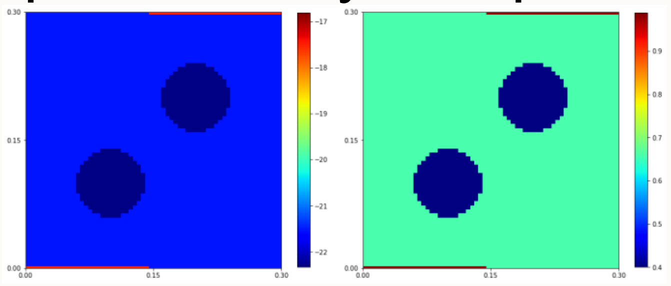
A novel method is proposed, where racetracking is part of the experiment. The fibre bundle permeability is derived by applying an inversion algorithm to recorded pressure data.

To avoid capillary effects, saturated flow experiments can be run. For these, the amount of data used in the inversion is reduced compared to transient experiments. In addition, only sensor data can be used, not flow front data.

The accuracy of results depends on the number of sensors and sensor placement.

Additional explanation

(Unknown) true distribution of permeability and porosity

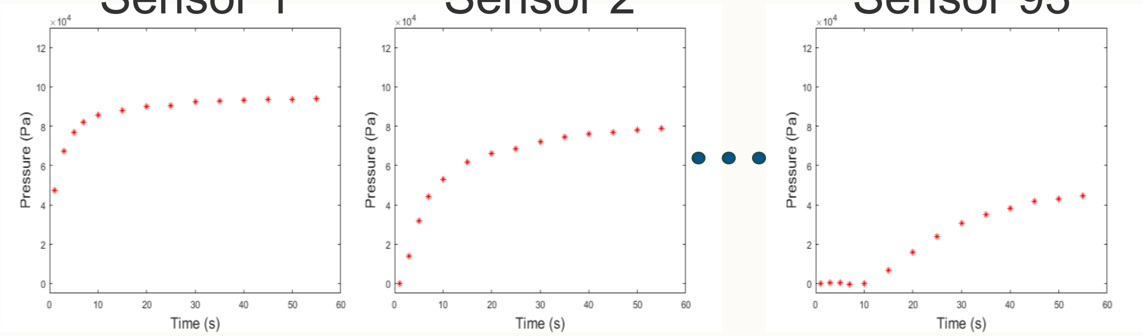


$\log K^\dagger$ $\Phi^\dagger$

experiment

Recorded pressure-time curves

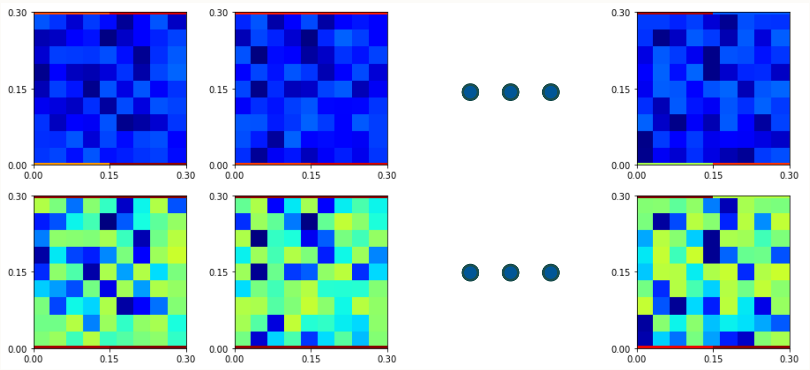
Sensor 1 Sensor 2 Sensor 93

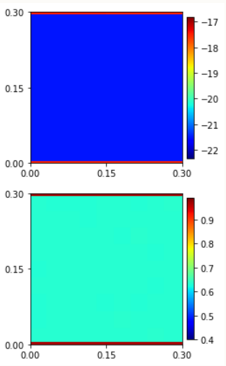


Recover local properties

Ensemble of J samples

Mean

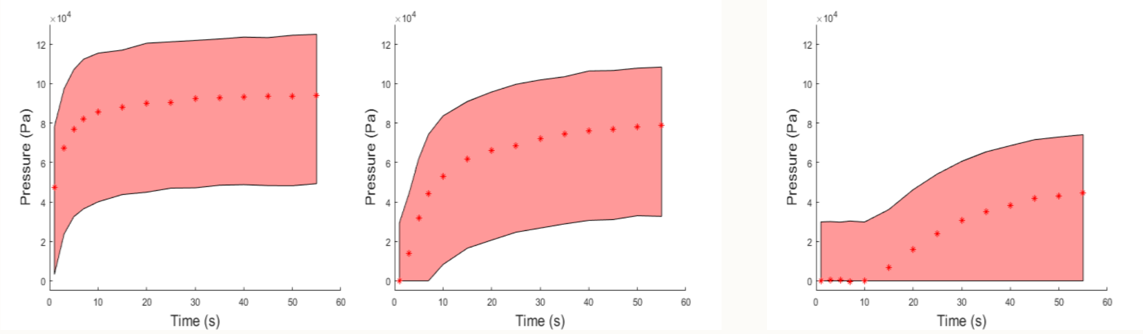




First guess (“prior”)

CVFEM simulations

Results from all J samples



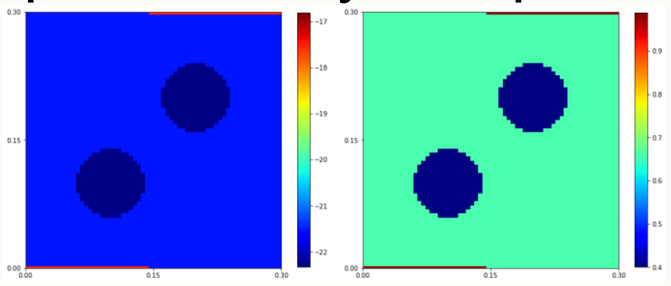
Not a good match with recorded data

Update ensemble

Additional explanation

(Unknown) true distribution of permeability and porosity

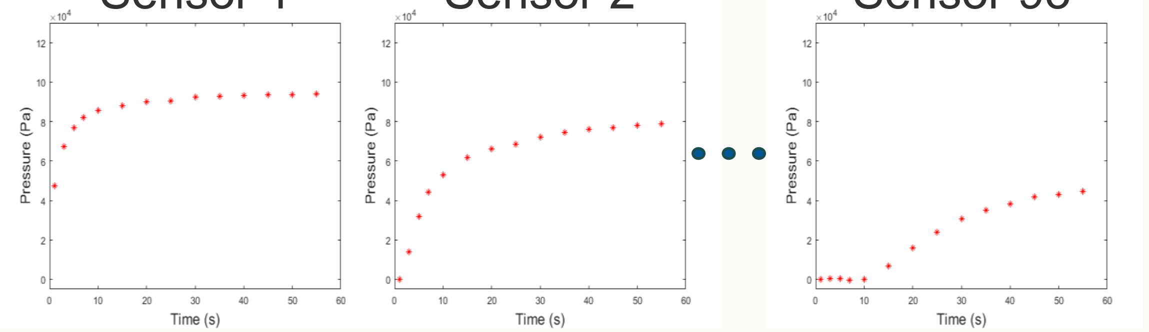
$\log K^{\dagger}$ $\Phi^{\dagger}$



experiment

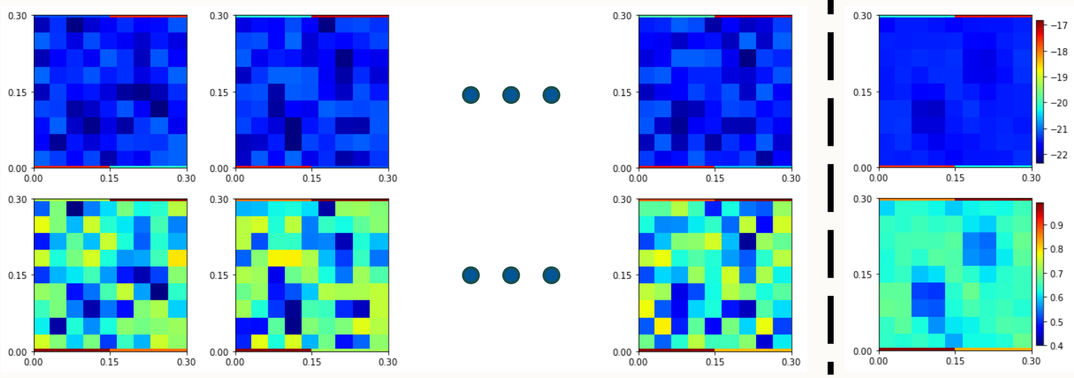
Recorded pressure-time curves

Sensor 1 Sensor 2 Sensor 93



Recover local properties

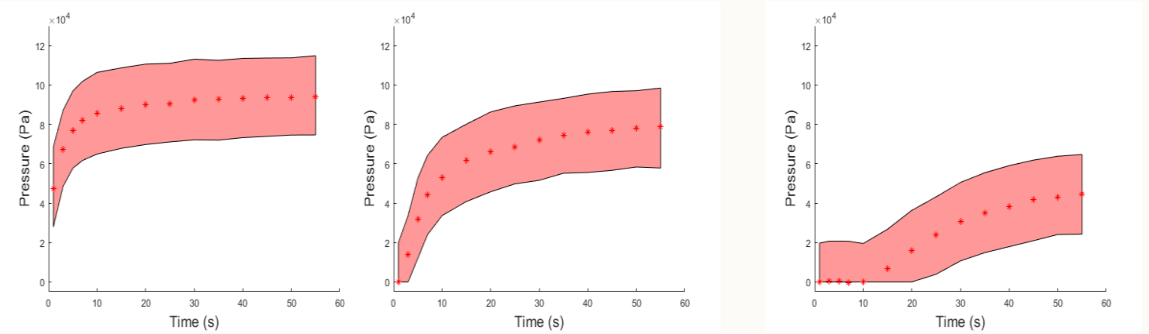
Ensemble of J samples | Mean



updated

CVFEM simulations

Results from all J samples



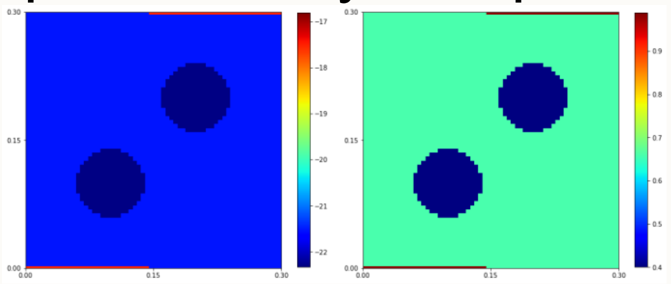
Improved, but still not a good match

Update ensemble

Additional explanation

(Unknown) true distribution of permeability and porosity

$\log K^{\dagger}$

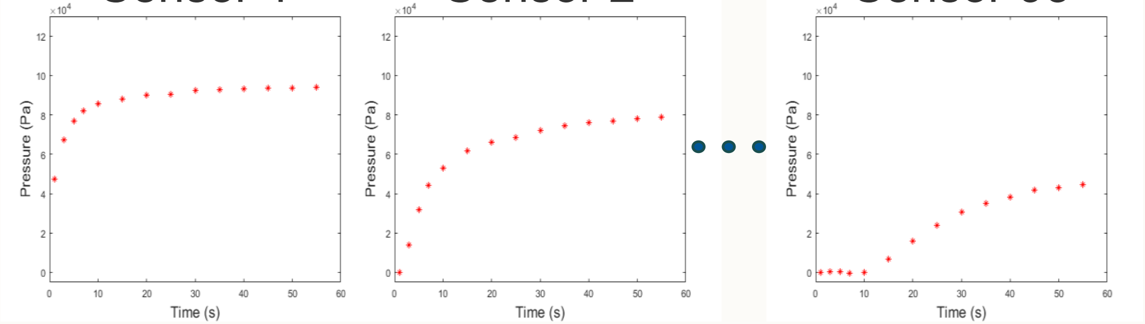


$\Phi^{\dagger}$

experiment

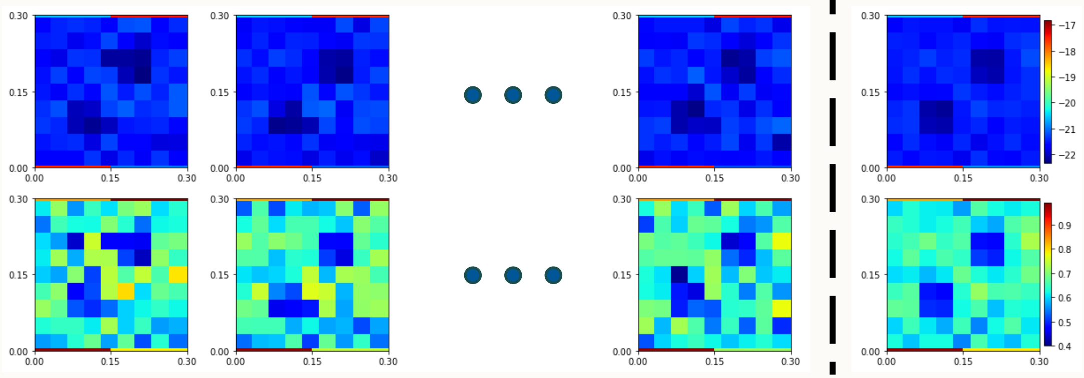
Recorded pressure-time curves

Sensor 1 Sensor 2 Sensor 93



Recover local properties

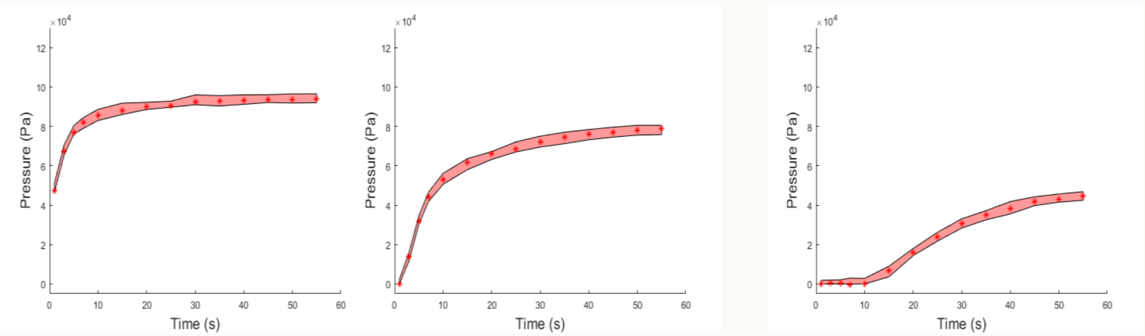
Ensemble of J samples | Mean



updated

CVFEM simulations

Results from all J samples



Acceptable match

➡ Ensemble is “posterior” approximation