GAS-LIQUID FLOW MODELING IN COLUMNS EQUIPPED WITH STRUCTURED PACKING SEEN AS A BI-STRUCTURED POROUS MEDIA

C. Soulaine[1] and M. Quintard[1,2]

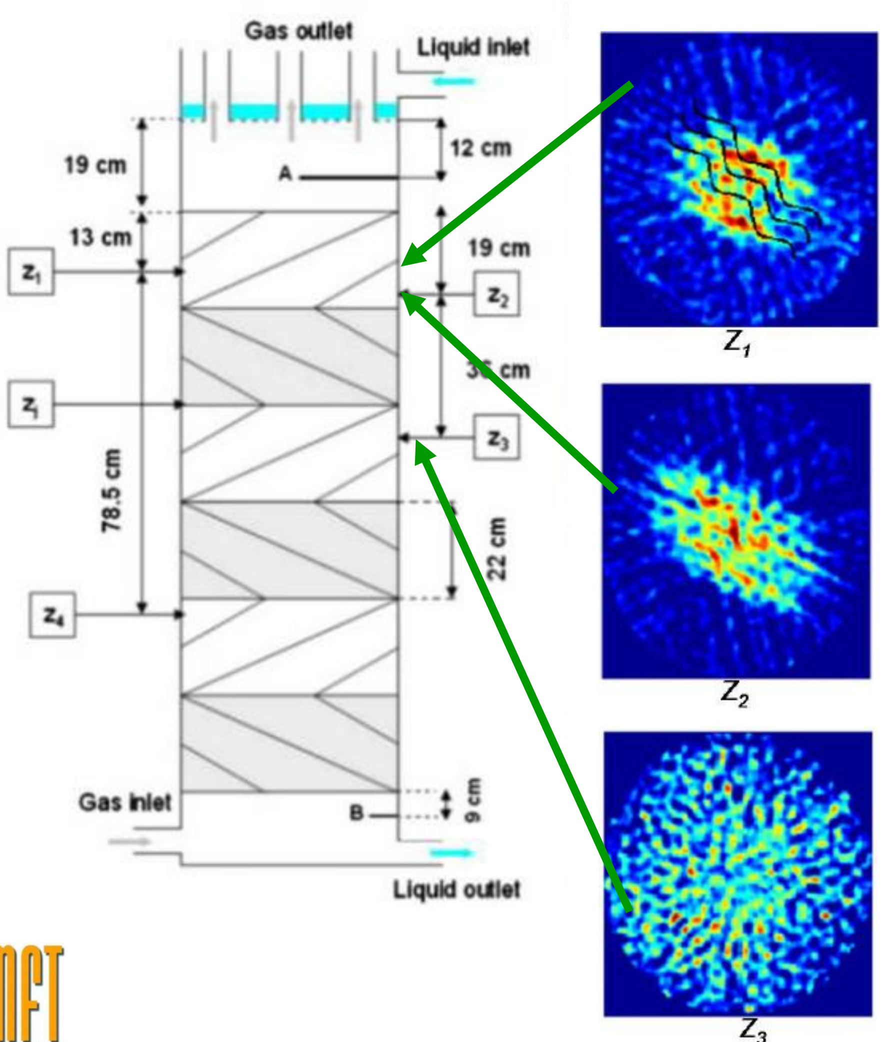
[1] Institut de Mécanique des Fluides de Toulouse, France
[2] C.N.R.S, France

13AIChE Annual Meeting, San Francisco, CA

AIChE 2013
November, 5th

The problem of the radial liquid spreading

"Experimental study of liquid spreading in structured packings"
Fourati et al. (2012)



- **MellaPak 250.X** (Sulzer Chemtech)

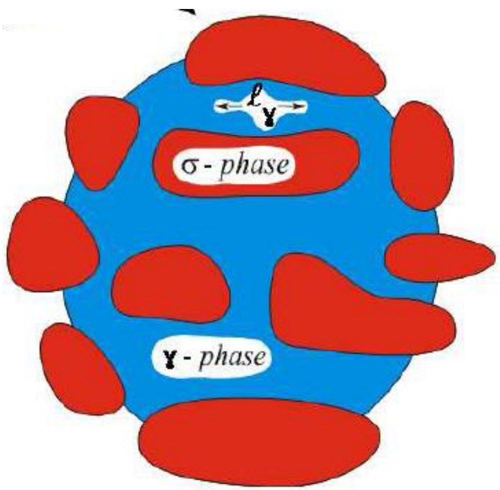
- Corrugations angle = 30° from the vertical axis
- Pileup of 6 packings 22cm height, rotated by 90° from the previous packing
- source point inlet at the top of the first pack

- In the first pack, the liquid flow according to the sheets orientation.
- After several packs, the liquid distribution is almost homogeneous.
- **How to model this radial dispersion from a macroscopic point of view ?**

Notion of scale in porous media

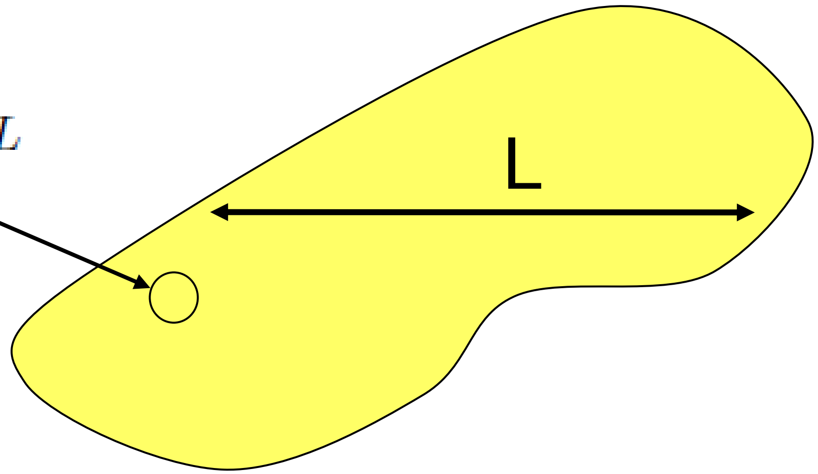
13AIChE Annual Meeting, San Francisco, CA

Pore-scale / REV



Macro-scale

$l_\alpha \ll L$



- Mathematical problem with boundary conditions at fluid/solid interface
  (1 cell = fluid OR solid)

  Ex: Stokes's problem

- Averaged equations
  (1 cell = fluid AND solid)

  Ex: Darcy's law (velocity averaged on a REV)

We can use **upscaling** method to get macroscopic laws from pore-scale physics (cf. *Whitaker 1986; Sanchez-Palencia 1982*. for Darcy's law demonstration from Stoke's problem)

Preliminaries: the bi-structured porous media

- *Examples of bi-structured porous media*
- *Notion of scale in porous media*
- *Single phase flow model in bi-structured porous media*

Gas-liquid flow modeling in structured packings using a two-liquid approach

- *Review of some experiments*
- *Mathematical model and multiphase permeabilities evaluation*
- *Comparaison of simulations results with experimental data*

Conclusion and perspectives

Preliminaries: the bi-structured porous media

- *Examples of bi-structured porous media*
- *Notion of scale in porous media*
- *Single phase flow model in bi-structured porous media*

Gas-liquid flow modeling in structured packings using a two-liquid approach

- *Review of some experiments*
- *Mathematical model and multiphase permeabilities evaluation*
- *Comparaison of simulations results with experimental data*

Conclusion and perspectives

What is a bi-structured porous media ?

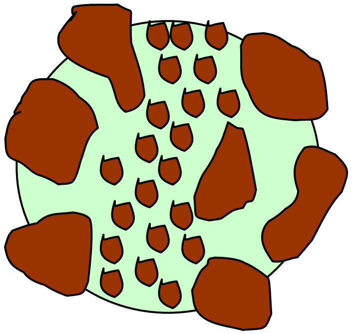
« (…) the porous medium itself exhibits a distinct two-region topology, e.g., as a consequence of a contrast of porosity or a difference in the pore structure geometry. Herein, we will use the term bi-structured *to describe these porous media, a term which represents a more general definition than the traditional dual-media or dual-porosity terminology.*

*With this definition, one may differentiate each region according to a number of different properties including the topology of the fluid flow. For example, in fractured media, fractures represent a zone of preferential flow whereas the amplitude of the velocity field in the matrix blocks is often orders of magnitude smaller.»**

* A two-pressure model for slightly compressible single phase flow in bi-structured porous media, *Chemical Engineering Sciences*, 2013, C. Soulaine, Y. Davit, M. Quintard

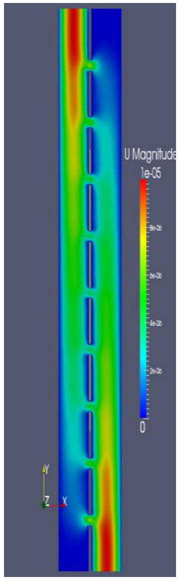
Examples of bi-structured porous media

dual-porosity media
(amplitude)

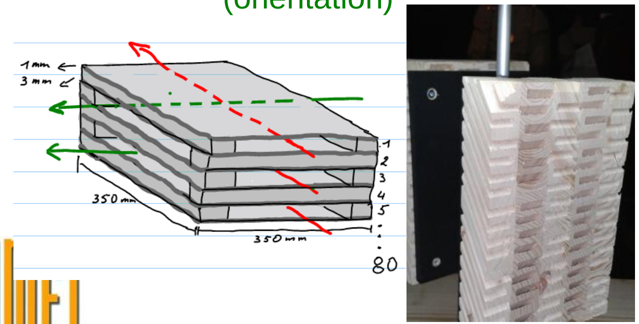


Structured packing
(orientation)

Fractured media
(photo by M. Musielak 2012)
(amplitude and/or orientation)



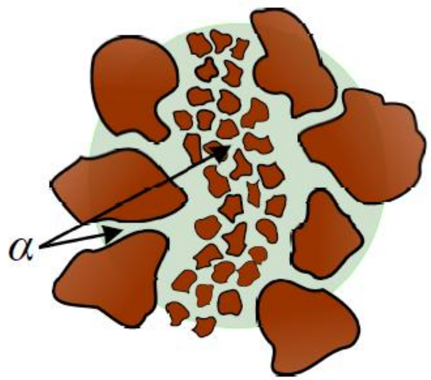
Air exchanger
(orientation)



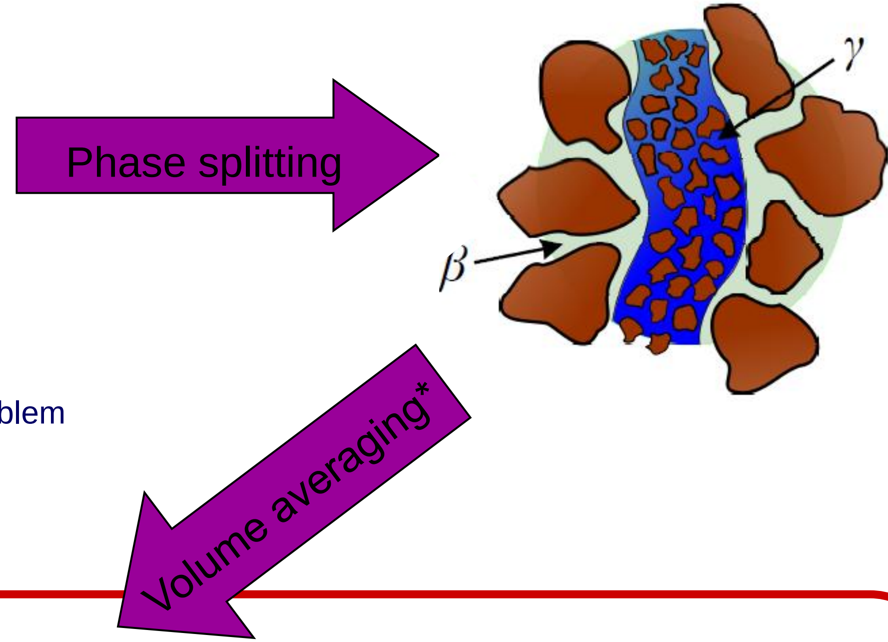
Ceramic perforated cylinders
(amplitude)

Tangential particle filter
(amplitude, due to BC)

Flow modeling in bi-structured porous media



Slightly compressible Stokes problem



$$\varepsilon_\gamma c \frac{\partial P_\gamma}{\partial t} + \nabla . \mathbf{U}_\gamma = \dot{m}$$

$$\varepsilon_\beta c \frac{\partial P_\beta}{\partial t} + \nabla . \mathbf{U}_\beta = -\dot{m}$$

$$\mathbf{U}_\beta = -\frac{k_\beta}{\mu} \nabla P_\beta \quad \mathbf{U}_\gamma = -\frac{k_\gamma}{\mu} \nabla P_\gamma$$

$$\dot{m} = \frac{h}{\mu} \left(P_\beta - P_\gamma \right)$$

* A two-pressure model for slightly compressible single phase flow in bi-structured porous media, *Chemical Engineering Sciences*, 2013, C. Soulaine, Y. Davit, M. Quintard

Preliminaries: the bi-structured porous media

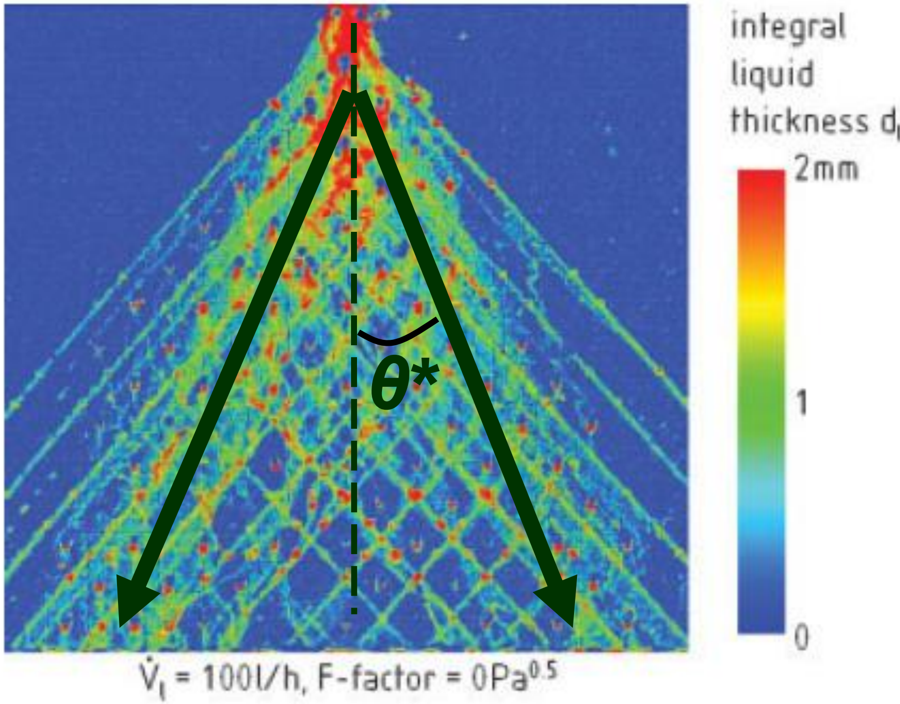
- *Examples of bi-structured porous media*
- *Notion of scale in porous media*
- *Single phase flow model in bi-structured porous media*

Gas-liquid flow modeling in structured packings using a two-liquid approach

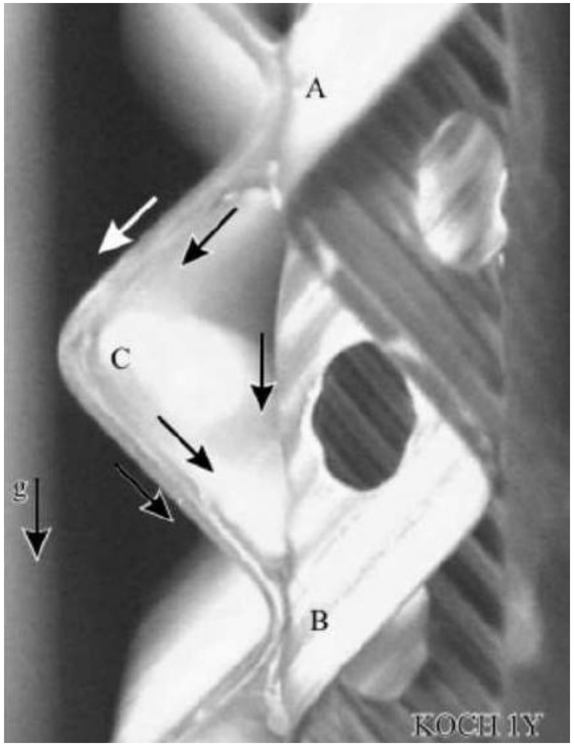
- *Review of some experiments*
- *Mathematical model and multiphase permeabilities evaluation*
- *Comparaison of simulations results with experimental data*

Conclusion and perspectives

Review of some experiments



Mahr and Mewes (2007)



Alekseenko (2008)

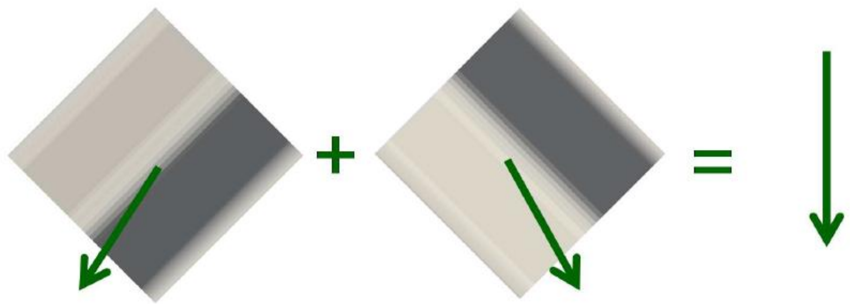
- We notice two preferential flow directions of the liquid, symmetric to the vertical axis and following a gravity angle θ^*,

- From a local point of view, *Alekseenko et al.* (2008) corroborate that each corrugated sheets are fully wetted (which form two distinct liquid films) and that meniscuses are present at each contact points, traducing the transfer of an amount of liquid from a sheet to another sheet.

Splitting of the liquid film into two separate phases

Analysis:

- A liquid film remains mostly on a corrugated sheet,
- Exchange of amount of liquid at the contact point between two adjacent sheets due to capillary effects,
- The liquid mass flow rate on each structure may be different (see the jet example),
- The usual generalized Darcy's law to two-phase flow can not catch the liquid spreading in the structured packing.



- *Mahr and Mewes (2007)* proposed to separate the liquid film into two separate phases that can exchange matter at the contact points,

- The hereby model is an heuristic extension of the single phase flow model in bi-structured porous media (see Part 1) to gas-liquid,

- Following the theory of Part 1, the mass exchange term can be expressed as a difference between the liquid pressures:

$$\dot{m} = \frac{h}{\mu}\left(P_\beta - P_\gamma\right)$$

Gas-liquid flow model in structured packing

13AIChE Annual Meeting, San Francisco, CA

Generalized Darcy's law to 3 fluids (1 gas, 2 liquids with the same physical properties) :

$$\varepsilon \frac{\partial S_\gamma}{\partial t} + \nabla . \mathbf{U}_\gamma = 0, \qquad \mathbf{U}_\gamma = -\frac{\mathbf{K}_\gamma}{\mu_\gamma} . \left(\nabla P_\gamma - \rho_\gamma \mathbf{g} \right),$$

$$\varepsilon \frac{\partial S_{\beta_1}}{\partial t} + \nabla . \mathbf{U}_{\beta_1} = \dot{m}, \qquad \mathbf{U}_{\beta_1} = -\frac{\mathbf{K}_{\beta_1}}{\mu_\beta} . \left(\nabla P_{\beta_1} - \rho_\beta \mathbf{g} \right),$$

$$\varepsilon \frac{\partial S_{\beta_2}}{\partial t} + \nabla . \mathbf{U}_{\beta_2} = -\dot{m}. \qquad \mathbf{U}_{\beta_2} = -\frac{\mathbf{K}_{\beta_2}}{\mu_\beta} . \left(\nabla P_{\beta_2} - \rho_\beta \mathbf{g} \right).$$

- Introducing capillary laws (type *Brooks and Corey)*, the liquid mass exchange term reads

$$\dot{m} = -\frac{h}{\mu_\beta} \left(p_{c_1} - p_{c_2} \right) = \frac{h p_{c0}}{\mu_\beta} \left(S_{\beta_1}^{\frac{1}{\lambda}} - S_{\beta_2}^{\frac{1}{\lambda}} \right)$$

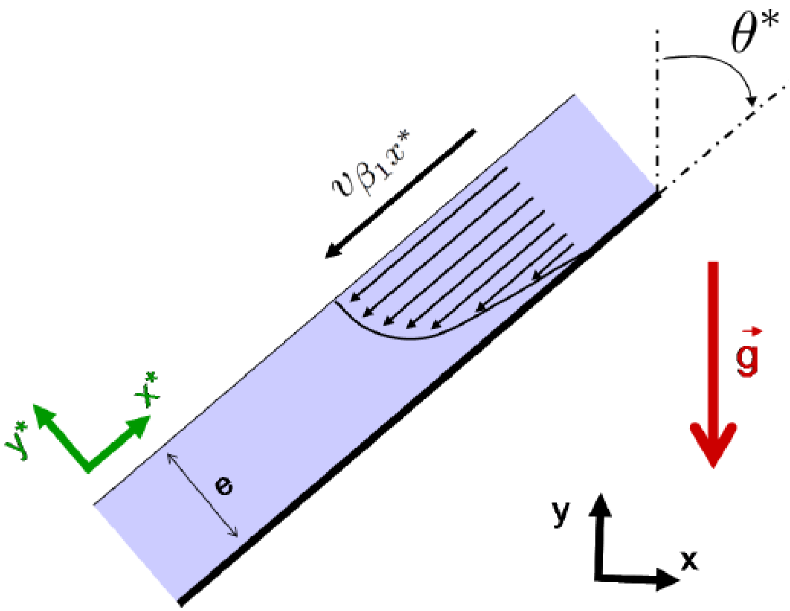
- The 3-phase flow in anisotropic porous media solver is coded using the OpenFOAM® technology with an IMPES method (gas pressure implicit, liquid saturations explicit)

How to evaluate the regional multiphase permeability tensors ?

INSTITUT DE MECANIQUE DES FLUIDES DE TOULOUSE

Inclined plane analogy

- Evaluation of multiphase permeability tensors:



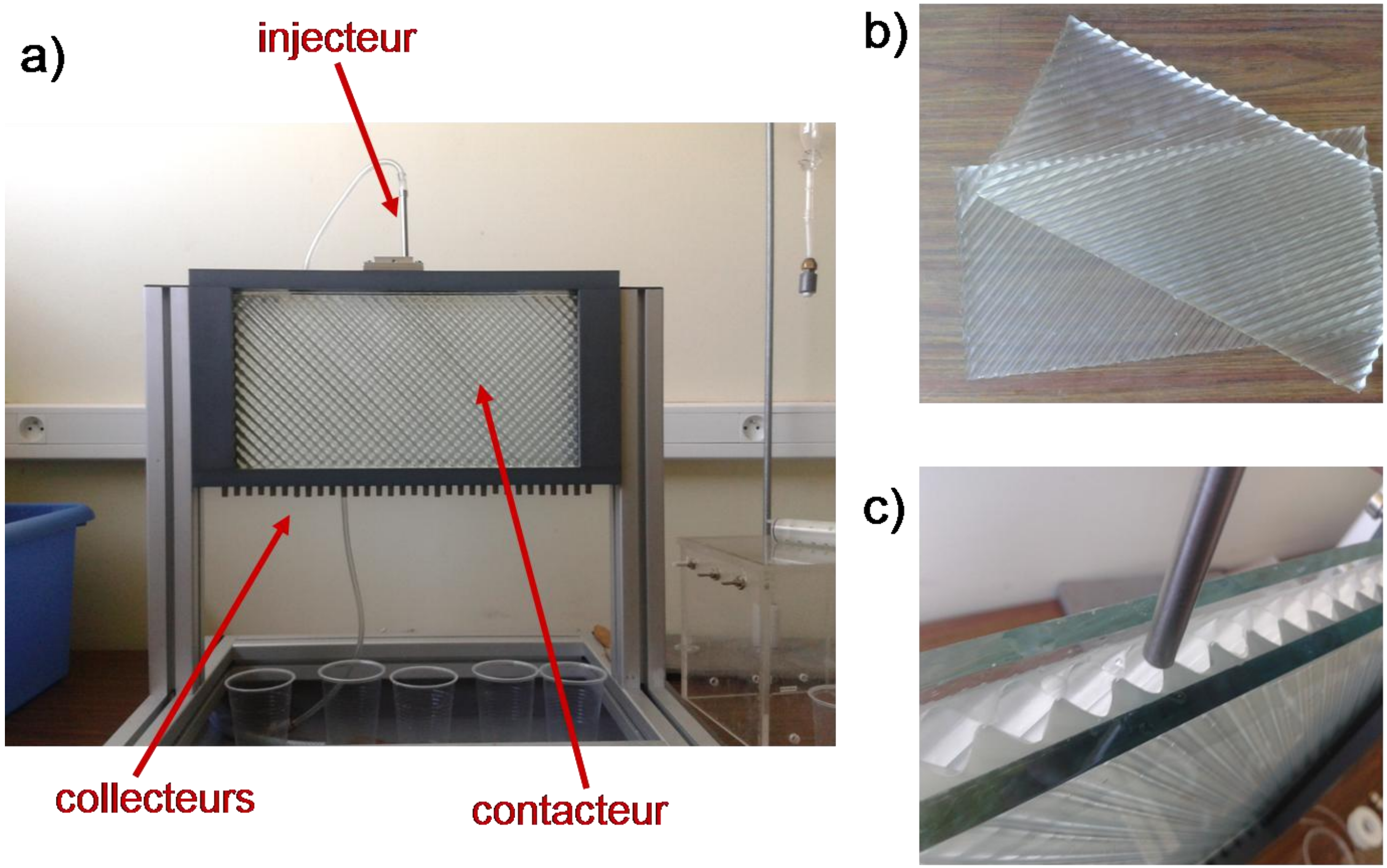
$$\mathbf{K}_{\beta_1} = \frac{K_0}{2} S_{\beta_1}^3 \begin{pmatrix} \cos^2(\theta^*) & \cos(\theta^*)\sin(\theta^*) & 0 \\ \cos(\theta^*)\sin(\theta^*) & \sin^2(\theta^*) & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\mathbf{K}_{\beta_2} = \frac{K_0}{2} S_{\beta_2}^3 \begin{pmatrix} \cos^2(\theta^*) & -\cos(\theta^*)\sin(\theta^*) & 0 \\ -\cos(\theta^*)\sin(\theta^*) & \sin^2(\theta^*) & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- Analytical formula of the gravity angle that depends on the 3D geometric features of the unit-cell:

$$\theta^* = \arccos\left(\frac{\sin^2\chi}{\sqrt{\sin^4\chi + \sin^2\theta\cos^2\theta\cos^4\frac{\beta}{2}}}\right)$$

Comparison with experience n°1 (1/2)



Manufactured at IMFT (Ruddy Soeparno)

Sheets in transparent PDMS

Dimensions = 15*30 cm

Corrugation angle = 45°

→ Gravity angle $\theta^* \approx 31^\circ$

Comparison with experience n°1 (2/2)

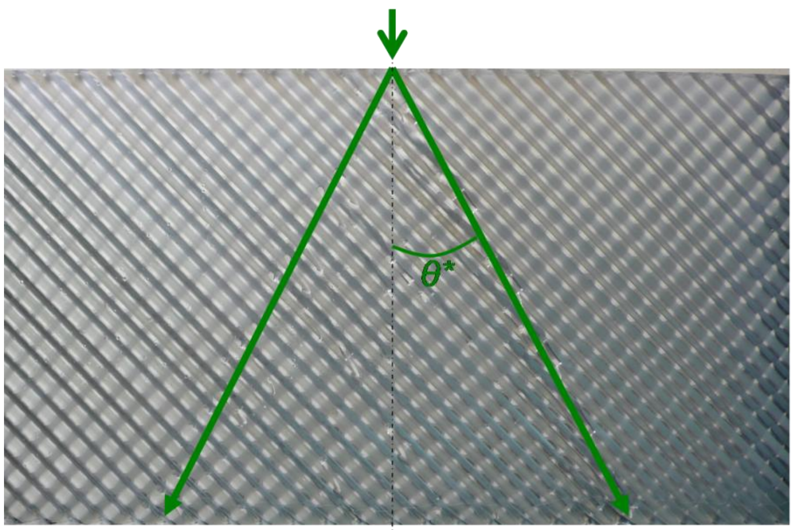
Experimental parameters:

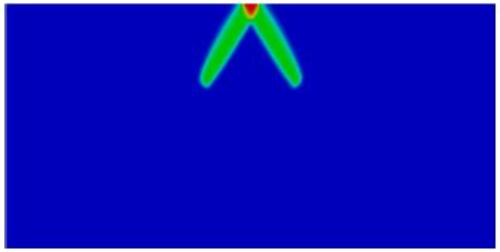
Fluid = wetting oil *(Lubrilog LY F 15)*

Inlet mass flow rate = 20mL/min

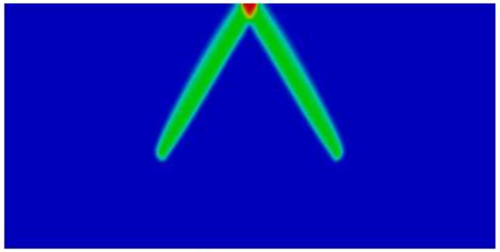
Observations:

- We notice 2 trickles of liquid flowing according to $\theta^* \approx 31^\circ$
- There is no liquid mass transfer between the sheets ($\dot{m} \approx 0$)

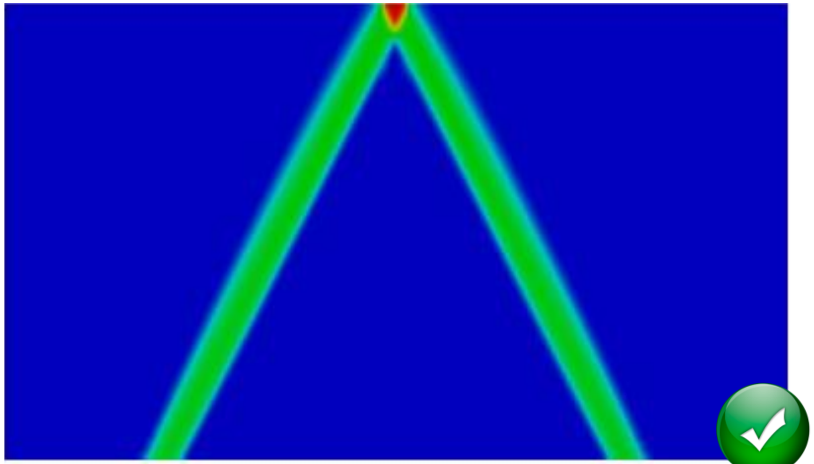




(a) t = 0,5 s

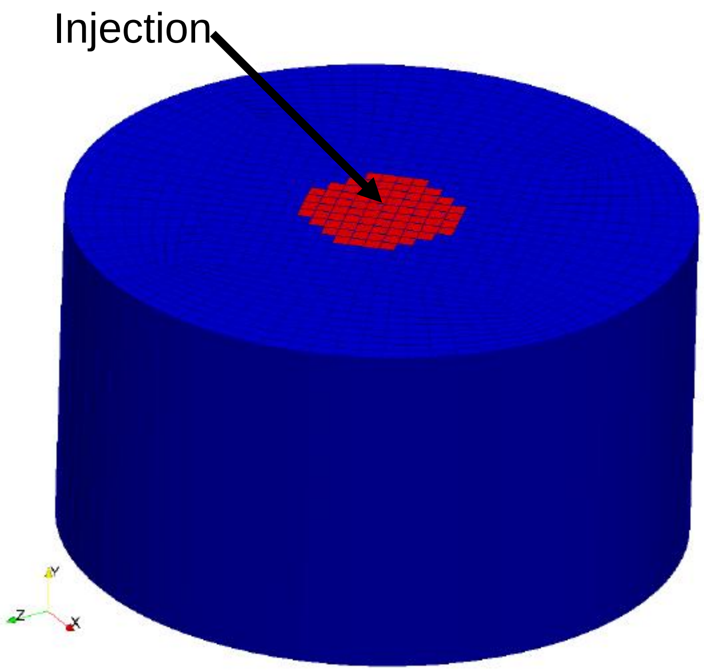


(b) t = 1 s

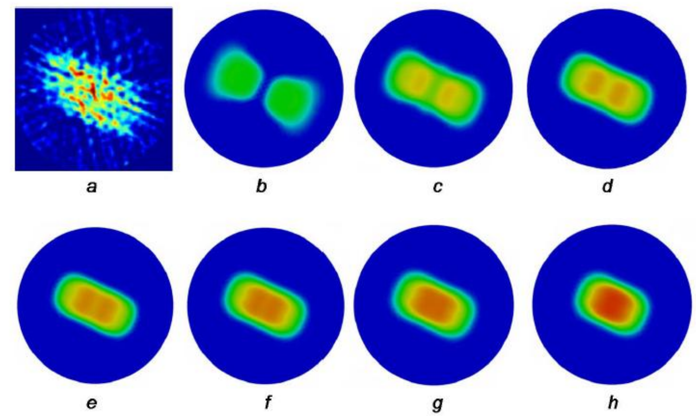


(d) t = 2 s

Comparison with experiment n°2 (1/3)



1 There are still some unknown parameters in the liquid mass transfer term. There are obtained from a sensitive analysis of *h, λ and* p_{c0} . Here are the results for $\lambda=2$ and $p_{c0}=0.1$ *kg/m/s*^{2}.



- The model behaves as a classical two-phase flow model when *h* is large (local equilibrium)

2 The flow in the following pack is obtained:

- Applying the relationship:

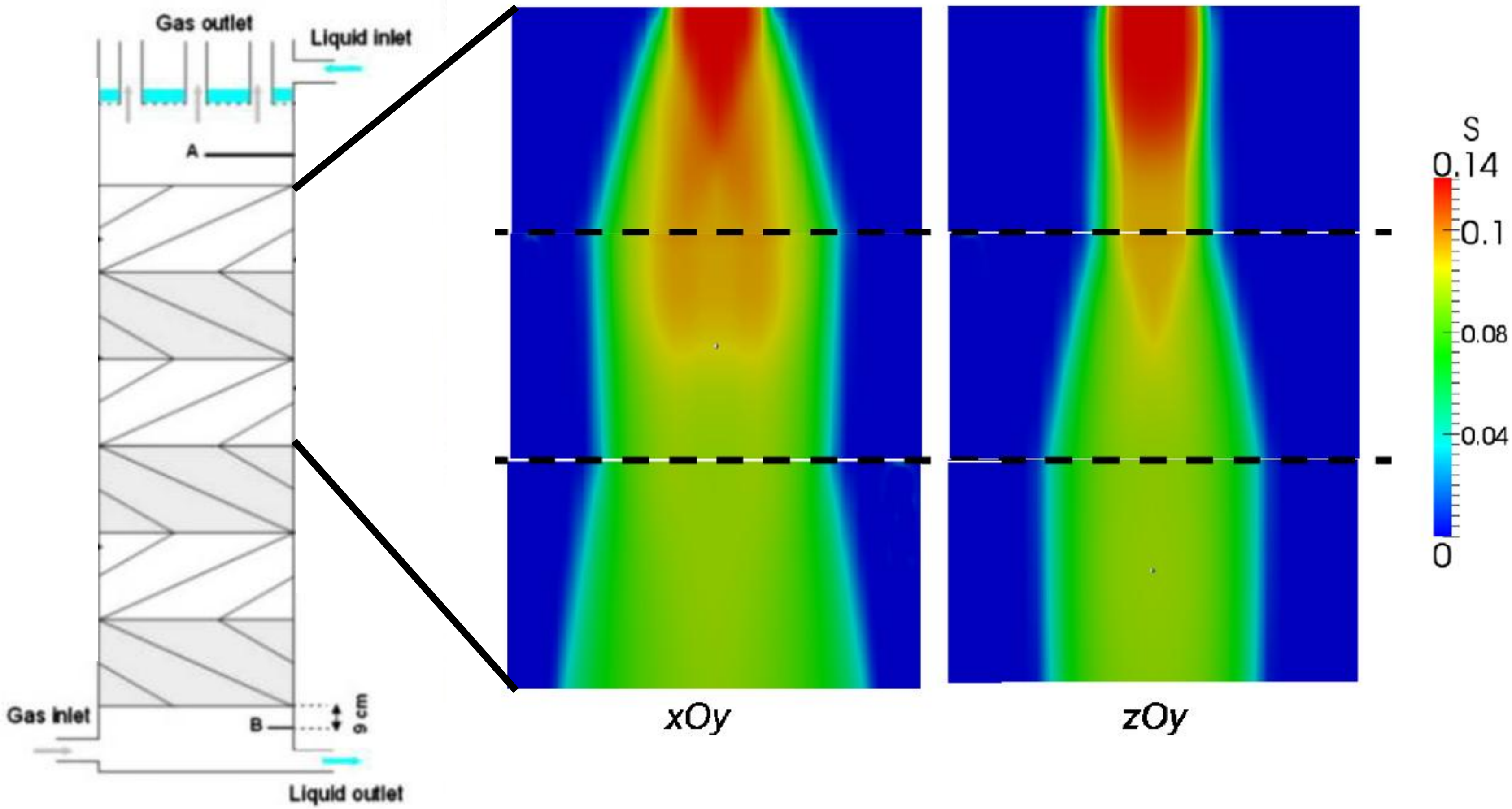
$$\langle \mathbf{v}_{\beta_1} \rangle^{n+1}_{\texttt{entrée}} = \langle \mathbf{v}_{\beta_2} \rangle^{n+1}_{\texttt{entrée}} = \frac{\langle \mathbf{v}_{\beta_1} \rangle^{n}_{\texttt{sortie}}}{2} + \frac{\langle \mathbf{v}_{\beta_2} \rangle^{n}_{\texttt{sortie}}}{2}$$

- Switching the permeabilities coefficients (x↔z)

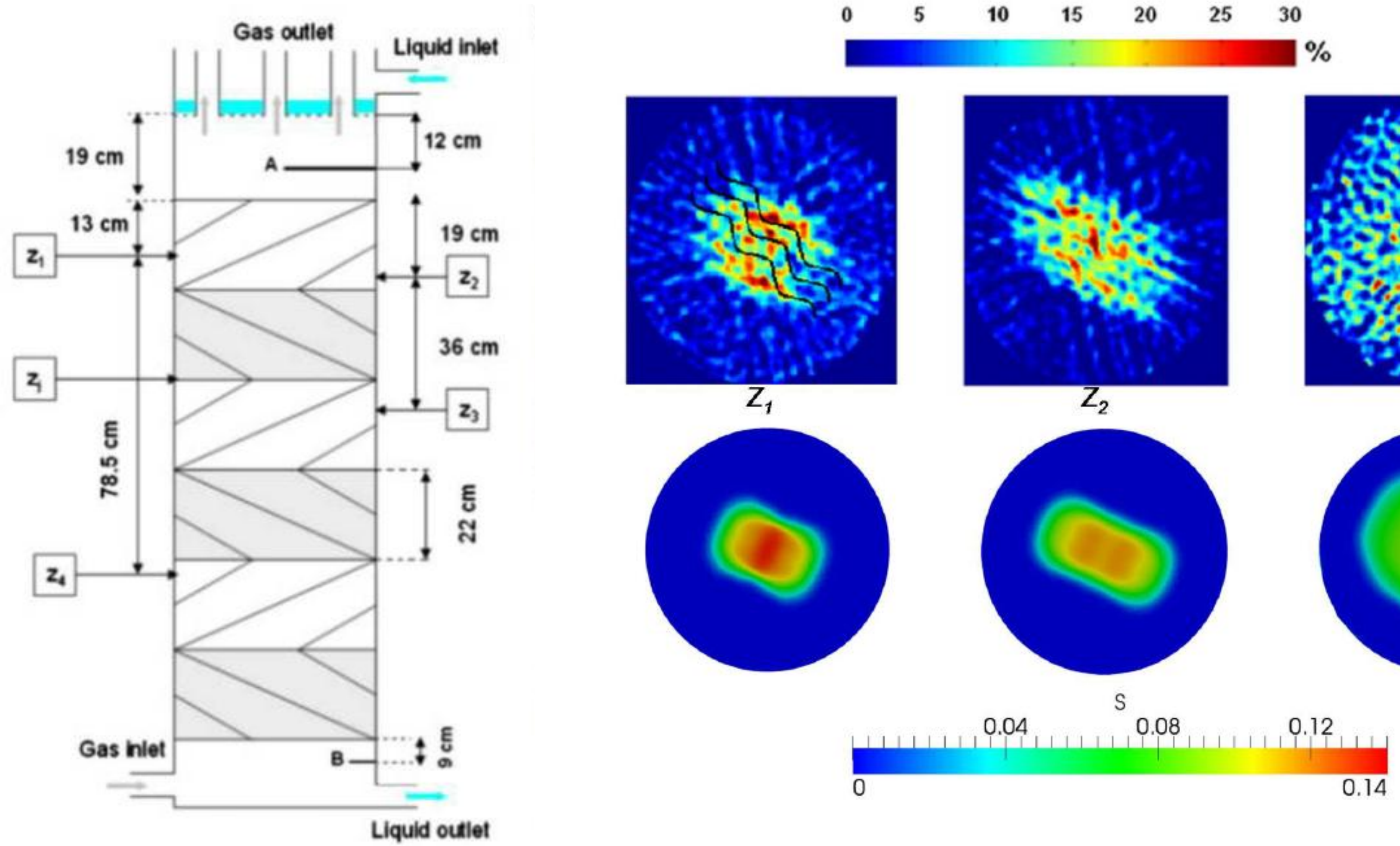
$$\begin{pmatrix} K^*_{xx} & K^*_{xy} & 0 \\ K^*_{yx} & K^*_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix} \longrightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & K^*_{yy} & K^*_{yz} \\ 0 & K^*_{zy} & K^*_{zz} \end{pmatrix}$$

3 The process is iterated for the next pack…

Comparison with experiment n°2 (2/3)



Comparison with experiment n°2 (3/3)



- The model can catch the liquid spreading mechanism in the structured packing
- Simulation results are less diffusive than experimental data (potential improvements of the model: calculation of the gravity angle and the permeability tensors from the real topology, shear-stress terms, inlet conditions, more accurate measurement of the exchange coefficient…)

Preliminaries: the bi-structured porous media

- *Examples of bi-structured porous media*
- *Notion of scale in porous media*
- *Single phase flow model in bi-structured porous media*

Gas-liquid flow modeling in structured packings using a two-liquid approach

- *Review of some experiments*
- *Mathematical model and multiphase permeabilities evaluation*
- *Comparaison of simulations results with experimental data*

Conclusion and perspectives

Conclusion and perspectives

- We have developed macroscale model for gas-liquid flow in structured packing. The two liquid films are seen as two continua that can exchange matter,

- It allows one to understand the mechanisms that lead to the liquid spreading (geometry + capillary effects),

- Simulations have been successfully compared to the tomography imaging by *Fourati et al. (2012),*

- Quantitative results are accessible if the effective parameters (permeability, capillary pressure, effective angle…) are estimated accurately, from experiment or pore-scale simulations.

Thank you for your attention...

cyprien.soulaine@gmail.com

fr.linkedin.com/in/csoulain/