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## Macro-scale modeling of two-phase flows within structured packings

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# Macro-scale modeling of two-phase flows within structured packings

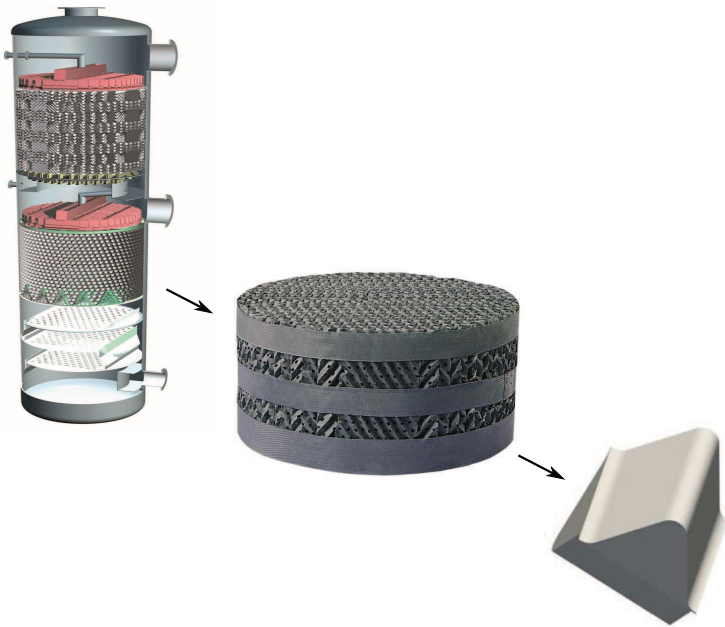
Sylvain Pasquier, Yohan Davit, Michel Quintard

Institut de Mécanique des Fluides de Toulouse (IMFT) - Université de Toulouse,  
CNRS-INPT-UPS, Toulouse FRANCE

June 6, 2016

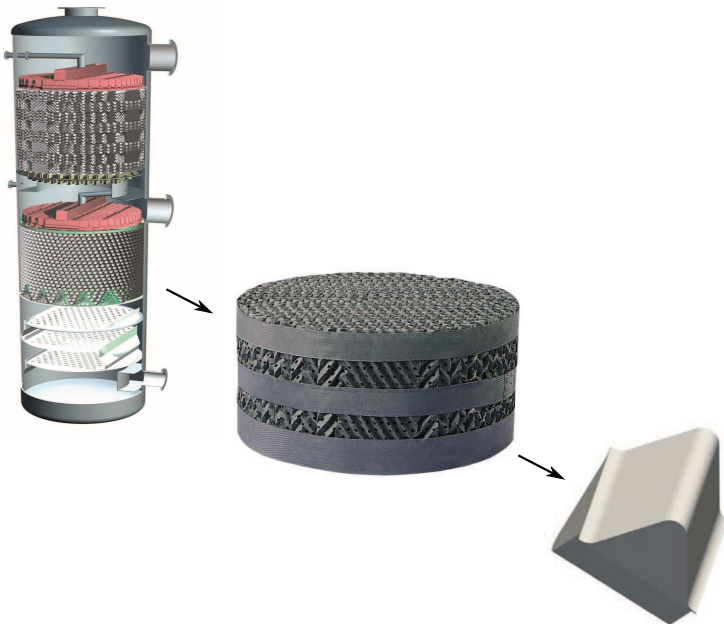


## Structured packings as a structured porous medium



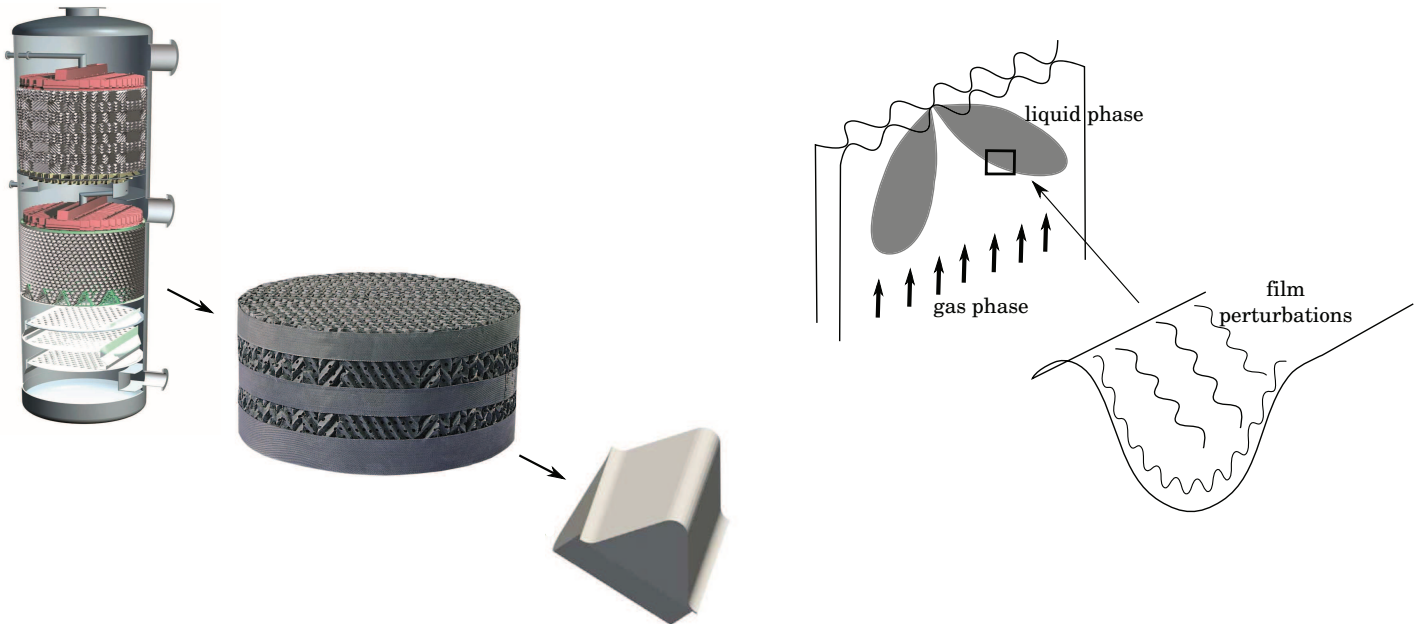
- A multi-scale process
- A complex interaction between gas and liquid
- A macro-scale model for the gas / liquid system ?

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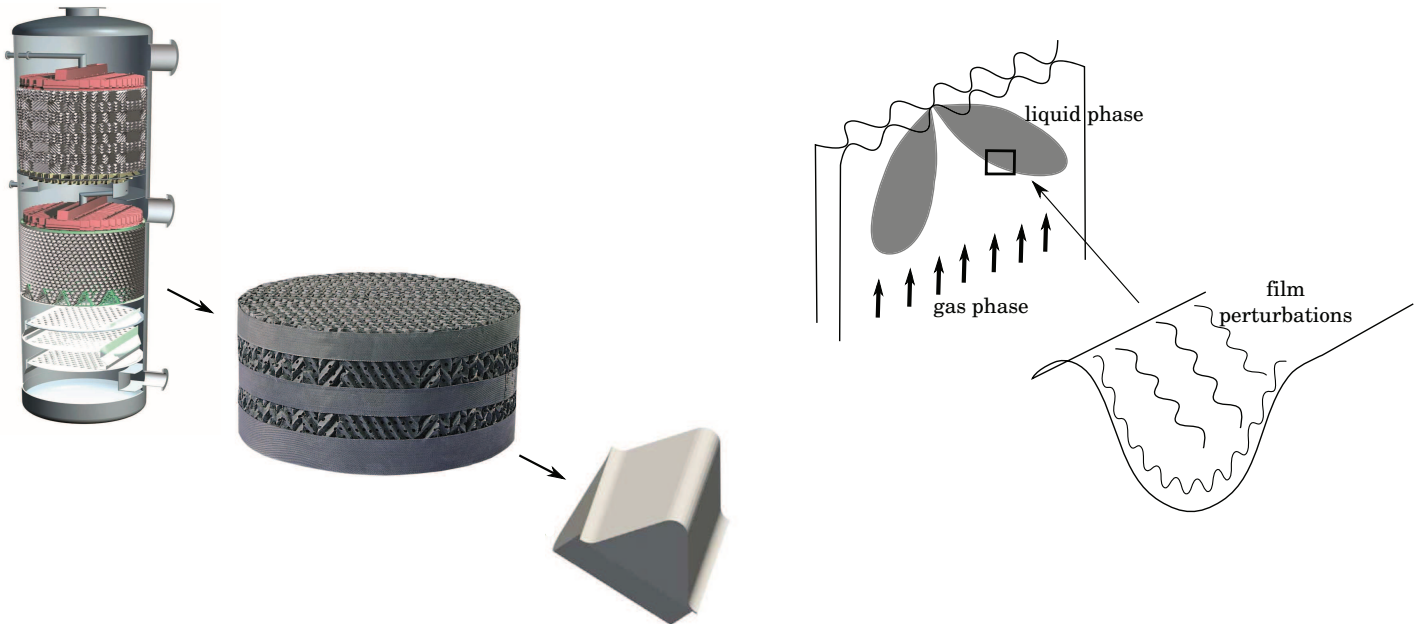
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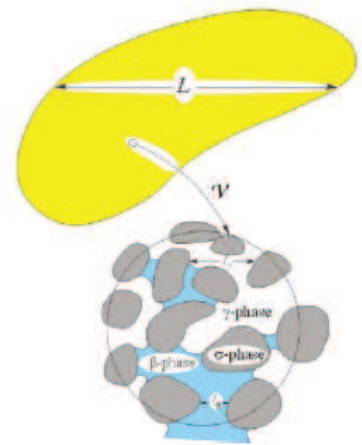


- A multi-scale process
- A complex interaction between gas and liquid
- **A macro-scale model for the gas / liquid system ?**

## Up-scaling method

### ■ Volume averaging method

$$\begin{array}{cc} \rho_g & \mathbf{u}_g \\ \rho_l & \mathbf{u}_l \end{array} \xrightarrow{\mathbf{K}_{\beta\gamma}^*} \begin{array}{cc} \langle \mathbf{u}_g \rangle & \langle p_g \rangle^g \\ \langle \mathbf{u}_l \rangle & \langle p_l \rangle^l \end{array}$$



### ■ Example: Darcy equation

$$\varepsilon \frac{\partial S_l}{\partial t} + \nabla \cdot \langle \mathbf{u}_l \rangle = 0$$

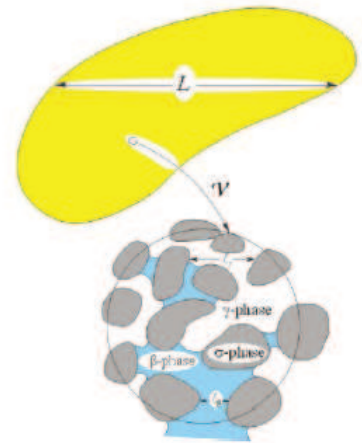
$$\langle \mathbf{u}_l \rangle = -\frac{\mathbf{K}_0}{\mu_l} \cdot \left( \nabla \langle p_l \rangle^l - \rho_l \mathbf{g} \right)$$



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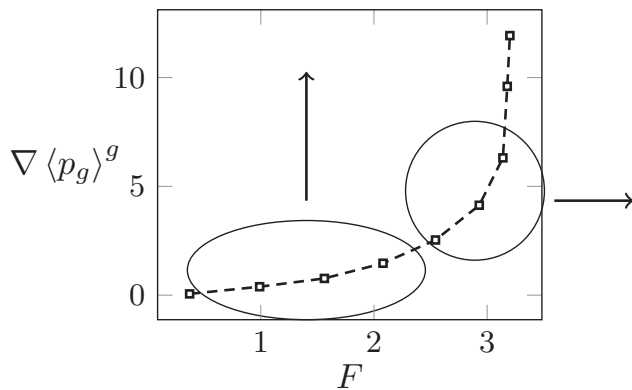
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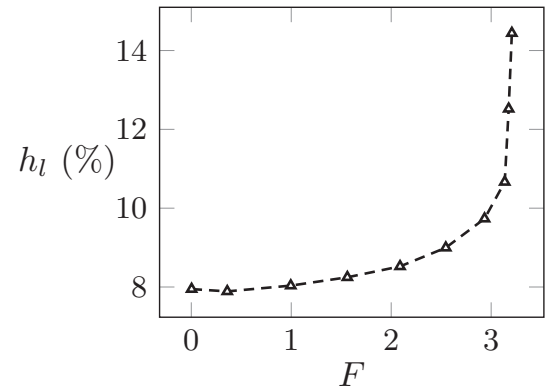
## Darcy's laws for gas/liquid flows in packings?

- Darcy-generalised equation (single phase approximation) Soullaine et al., Pasquier et. al.

$$\langle \mathbf{u}_g \rangle = -\frac{\mathbf{K}_0}{\mu_g} \cdot (\nabla \langle p_g \rangle^g - \rho_g \mathbf{g}) - \mathbf{F} \cdot \langle \mathbf{u}_g \rangle$$



Experimental data extracted from Brunazzi et al. (2002)



- Strong interaction between liquid and gas in the loading regime

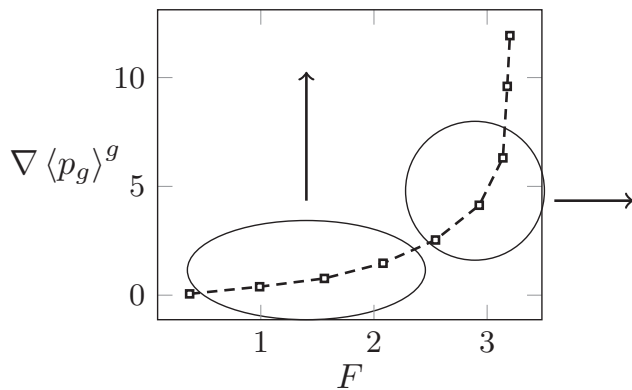
- pressure drop rise  $\nabla \langle p_g \rangle^g$
- liquid retention  $h_l$  increases

- Requires a coupled model at the macro-scale

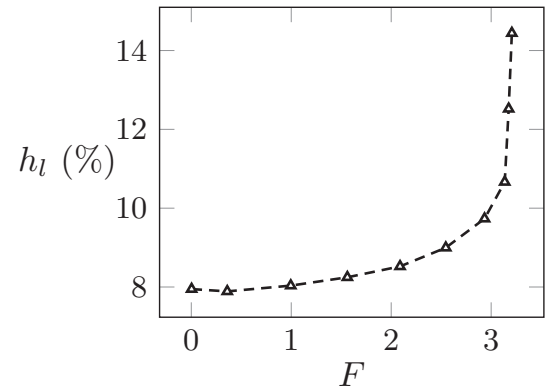
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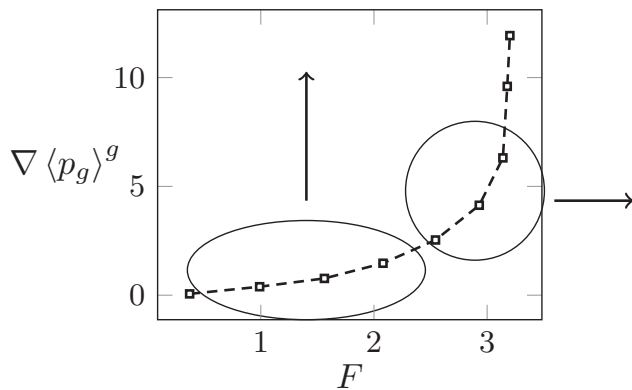
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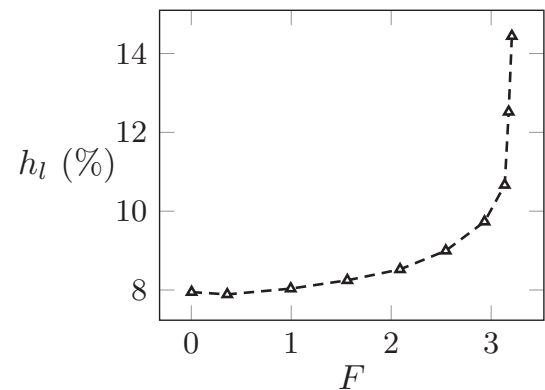
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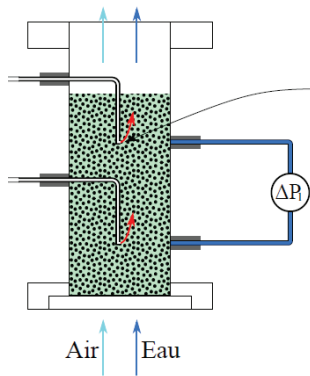
- Requires a coupled model at the macro-scale

## Up-scaling - Coupled model

- Viscous regime (Whitaker, Lasseux et al.)

$$\begin{pmatrix} \langle \mathbf{u}_l \rangle \\ \langle \mathbf{u}_g \rangle \end{pmatrix} = - \begin{pmatrix} \frac{\mathbf{K}_{ll}^*}{\mu_l} & \frac{\mathbf{K}_{lg}^*}{\mu_g} \\ \frac{\mathbf{K}_{gl}^*}{\mu_l} & \frac{\mathbf{K}_{gg}^*}{\mu_g} \end{pmatrix} \begin{pmatrix} \nabla \langle p_l \rangle^l \\ \nabla \langle p_g \rangle^g \end{pmatrix}$$

- Application: Two-phase flow in particle beds



- 1D resolution of the coupled system (OpenFoam)
- Closures of  $\mathbf{K}_{ll}^*$ ,  $\mathbf{K}_{gg}^*$ ,  $\mathbf{K}_{lg}^*$ ,  $\mathbf{K}_{gl}^*$  from experimental results

Calide experiment - IRSN - see Chikhi et al. 2016

## Numerical resolution : IMPES Method

- IMplicit Pressure Explicit Saturation
- Sequential resolution of an equation on pressure and on saturation

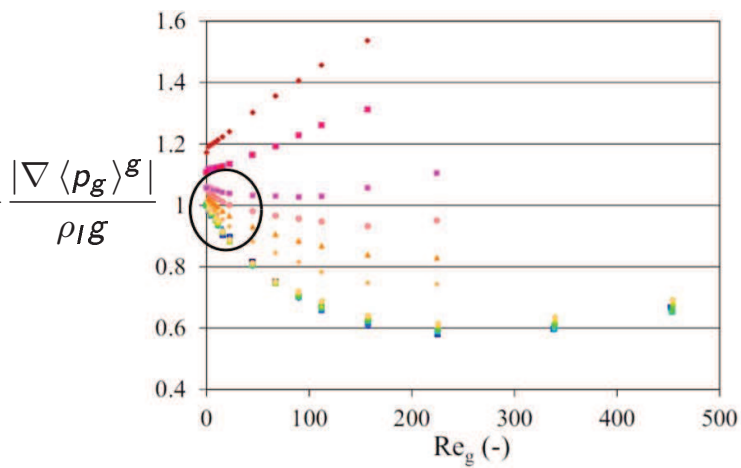
$$\frac{\partial}{\partial t} \begin{pmatrix} S_l \\ S_g \end{pmatrix} + \nabla \cdot \begin{pmatrix} \langle \mathbf{u}_l \rangle \\ \langle \mathbf{u}_g \rangle \end{pmatrix} = 0$$

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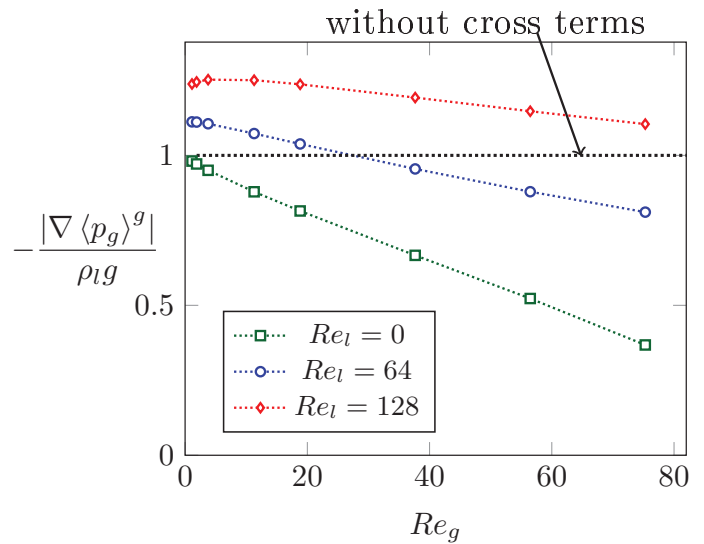
- Finite volume method
- Scalar or tensorial effective parameters  $\mathbf{K}^*$

## Up-scaling - Coupled model

### ■ Dimensionless pressure drop in the viscous regime



Experimental results Clavier et al. (2015)

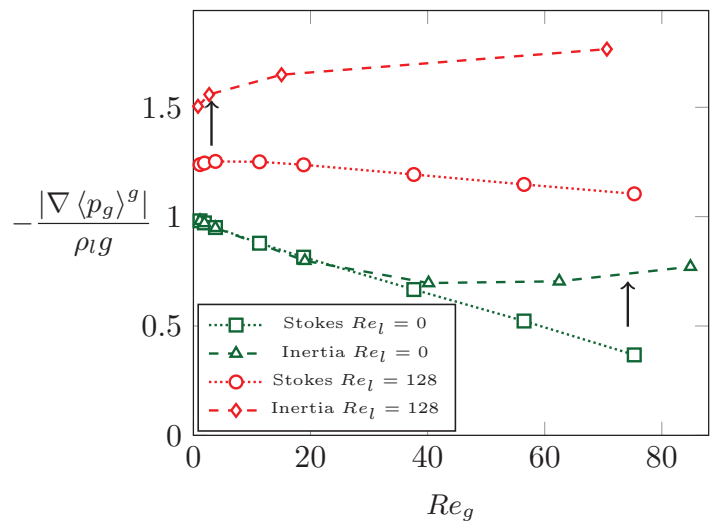
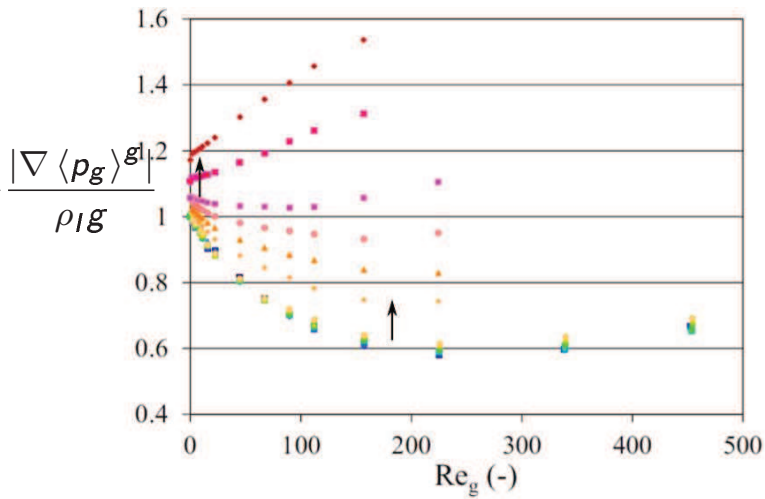


Numerical modeling of the coupled system (OpenFoam)

## Up-scaling - Coupled model

### ■ Inertial regime (Lasseux et al., 2008)

$$\begin{pmatrix} \langle \mathbf{u}_l \rangle \\ \langle \mathbf{u}_g \rangle \end{pmatrix} = - \begin{pmatrix} \frac{\mathbf{K}_{ll}^*}{\mu_l} & \frac{\mathbf{K}_{lg}^*}{\mu_g} \\ \frac{\mathbf{K}_{gl}^*}{\mu_l} & \frac{\mathbf{K}_{gg}^*}{\mu_g} \end{pmatrix} \begin{pmatrix} \nabla \langle p_l \rangle^l \\ \nabla \langle p_g \rangle^g \end{pmatrix} - \begin{pmatrix} \mathbf{F}_{ll}^* & \mathbf{F}_{lg}^* \\ \mathbf{F}_{gl}^* & \mathbf{F}_{gg}^* \end{pmatrix} \begin{pmatrix} \langle \mathbf{u}_l \rangle \\ \langle \mathbf{u}_g \rangle \end{pmatrix}$$





## Application to structured packings

### ■ 1D resolution of a air / water system



### ■ Comparison of a Darcy model and coupled models (viscous and inertial)

#### ■ Closures:

- Viscous: analogy to a liquid film in a cylinder tube
- Inertial: based on the closures from the Calide experiment

$$K_{gg} = K_0 (1 - S_l)^2 ; K_{ll} = K_0 S_l^3$$

$$K_{lg} = \frac{\mu_g}{\mu_l} \frac{S_l^2}{(1 - S_l)} ; K_{gl} = \frac{(1 - S_l)}{S_l}$$

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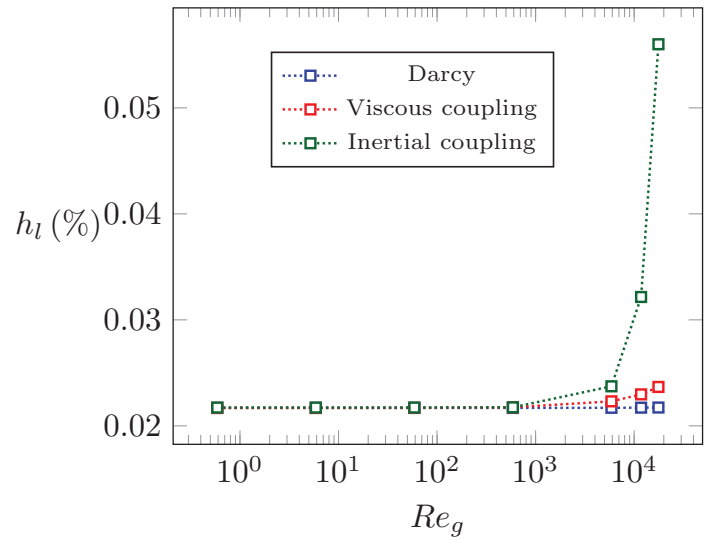
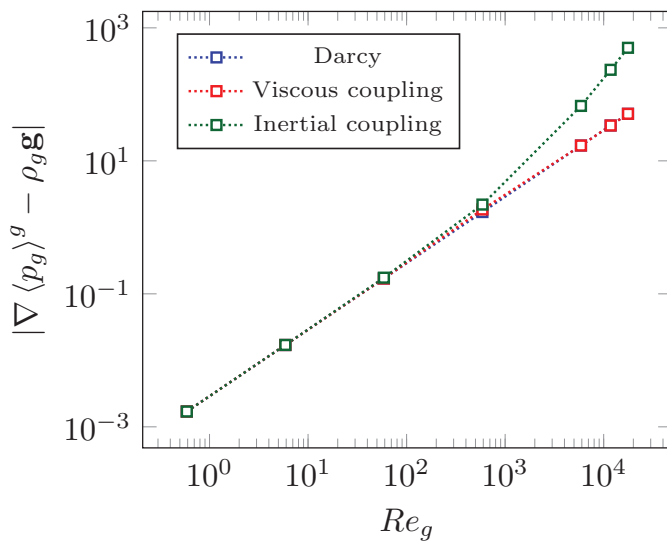
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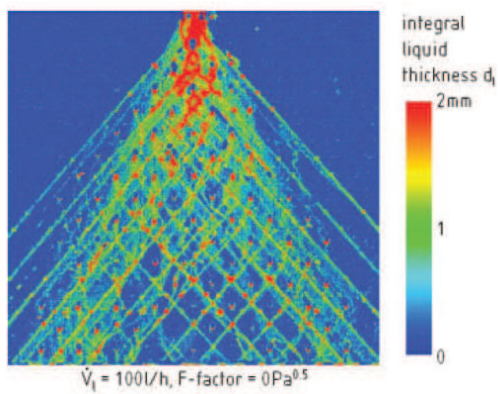
## Application to structured packings

- Analysis of the pressure drop  $\nabla \langle p_g \rangle^g$  and retention  $h_l$



- The inertial coupled model reflects the increase in retention and pressure drop
- Comparison from Suess and Spiegel (1991) for illustration

## Modeling of the dispersion of liquid? (1)



Mahr and Mewes (1999)

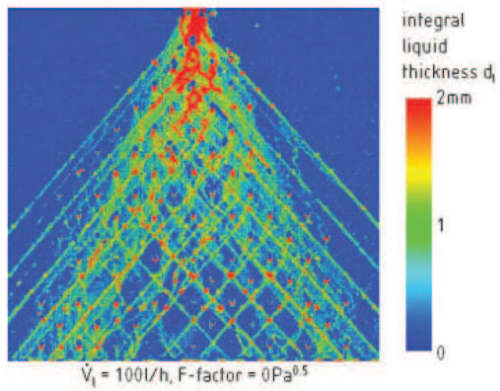
### ■ Tomography visualisation

Fourati et al. (2012)

Schug et al. (2015)

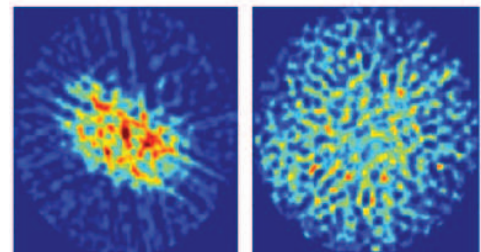
### ■ A two-equation model for the liquid phase

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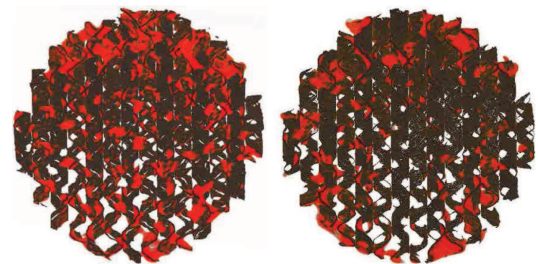


Mahr and Mewes (1999)

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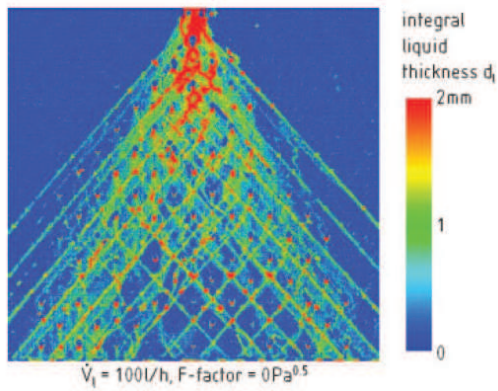
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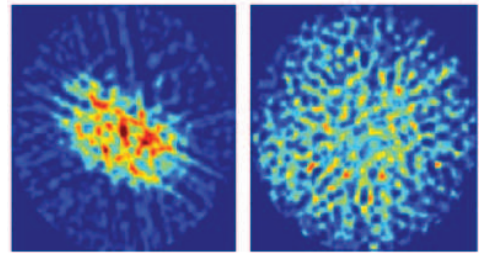
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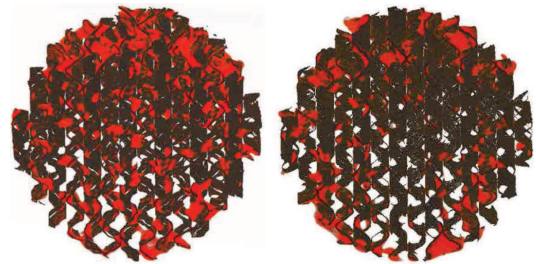


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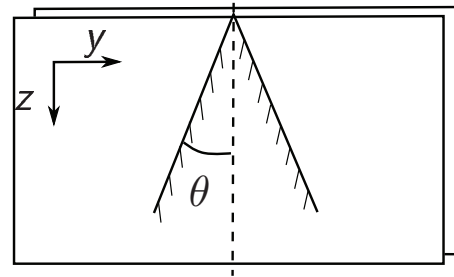
## Modeling of the dispersion of liquid? (2)

- Two-equation model for the liquid phase (Mahr and Mewes, Soulaïne et al.)

$$\langle \mathbf{u}_{l_1} \rangle = -\frac{\mathbf{K}_{ll_1}^*}{\mu_l} \cdot (\nabla \langle p_{l_1} \rangle^{l_1} - \rho_l \mathbf{g}) \quad ; \quad \langle \mathbf{u}_{l_2} \rangle = -\frac{\mathbf{K}_{ll_2}^*}{\mu_l} \cdot (\nabla \langle p_{l_2} \rangle^{l_2} - \rho_l \mathbf{g})$$

$$\mathbf{K}_{ll_i}^* = K_{ll_i}^* \begin{pmatrix} 0 & 0 & 0 \\ 0 & \cos^2 \theta^* \sin^2 \theta^* & \pm \cos \theta^* \sin \theta^* \\ 0 & \pm \cos \theta^* \sin \theta^* & \cos^2 \theta^* \sin^2 \theta^* \end{pmatrix}$$

$$i = 1, 2$$



- Liquid exchange at the contact points ?

$$\frac{\partial S_{l_1}}{\partial t} + \nabla \cdot \langle u_{l_1} \rangle = \dot{m} \quad ; \quad \frac{\partial S_{l_2}}{\partial t} + \nabla \cdot \langle u_{l_2} \rangle = -\dot{m}$$



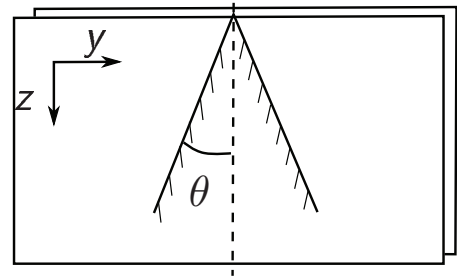
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$$\frac{\partial S_{l_1}}{\partial t} + \nabla \cdot \langle \mathbf{u}_{l_1} \rangle = \dot{m} \quad ; \quad \frac{\partial S_{l_2}}{\partial t} + \nabla \cdot \langle \mathbf{u}_{l_2} \rangle = -\dot{m}$$

## Modeling of the dispersion of liquid? (3)

- Closure of the liquid transfer at contact points?

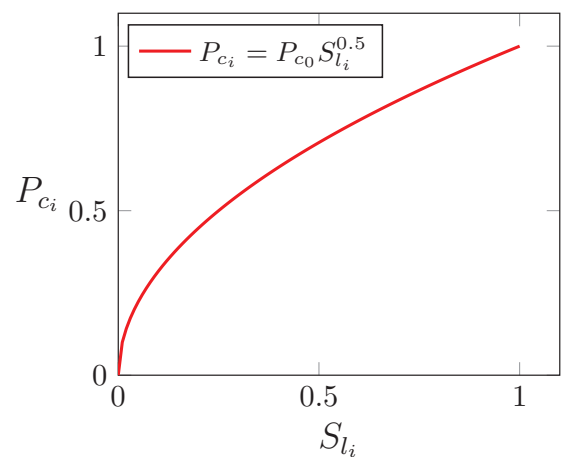
$$\dot{m} = h_1 \left( \langle p_{l_2} \rangle^{l_2} - \langle p_{l_1} \rangle^{l_1} \right)$$

- Assuming capillary pressure effects at contact points

$$P_{c_i}(S_i) = \langle p_g \rangle^g - \langle p_{l_i} \rangle^{l_i}$$

$$\dot{m} = h_1 (P_{c_2}(S_{l_2}) - P_{c_1}(S_{l_1}))$$

- Brooks and Corey relation

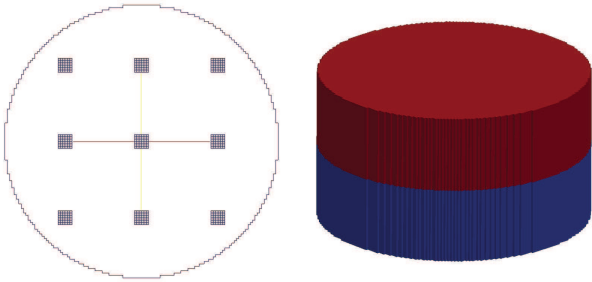


## Test case (1)

## ■ Variation of the liquid exchange coefficient

$h_1$	0.1	1	10
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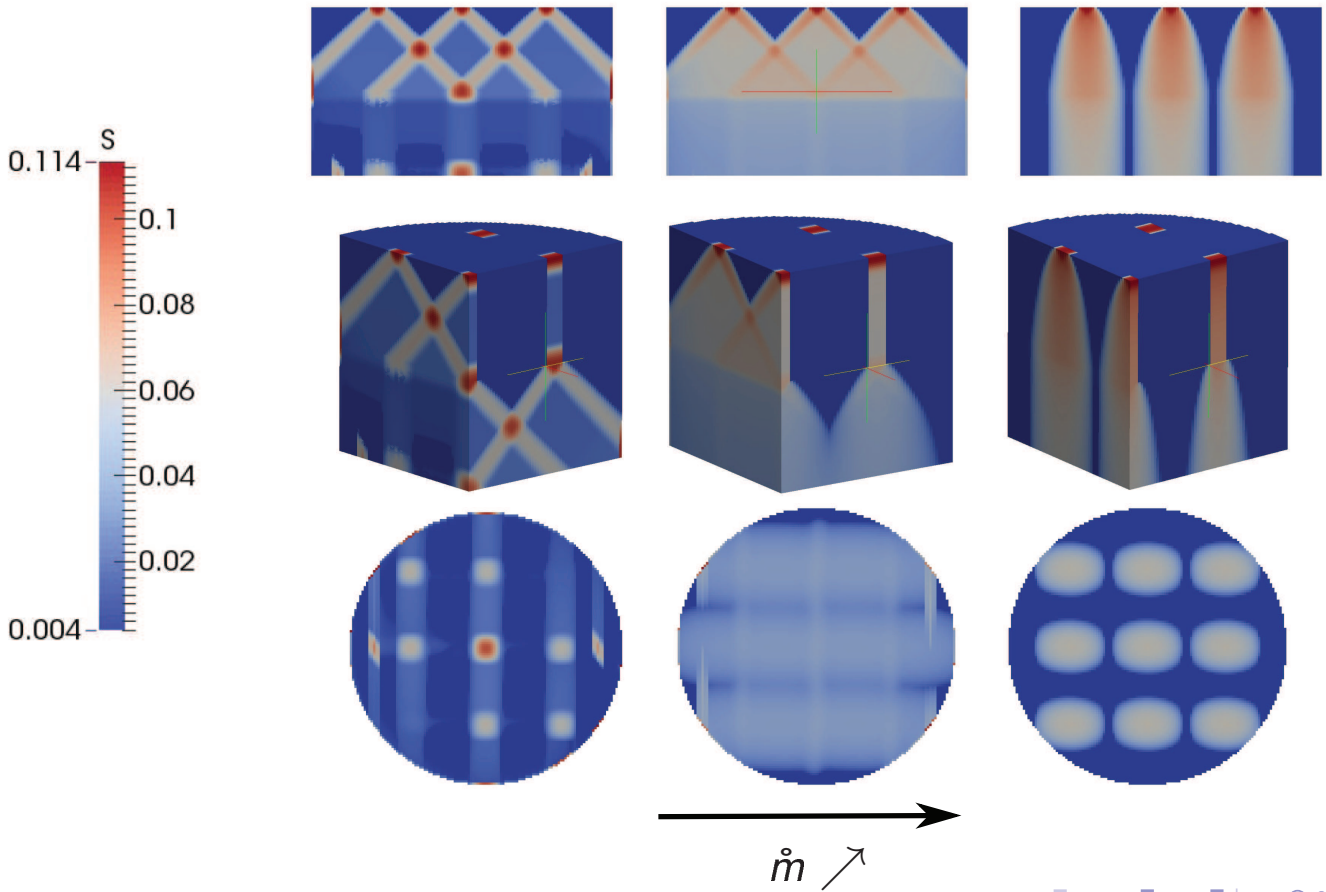
## ■ 9 injection points



$$K_{ll_i}^* = K_{ll_i}^* \begin{pmatrix} 0 & 0 & 0 \\ 0 & \cos^2 \theta^* \sin^2 \theta^* & \pm \cos \theta^* \sin \theta^* \\ 0 & \pm \cos \theta^* \sin \theta^* & \cos^2 \theta^* \sin^2 \theta^* \end{pmatrix} \quad i = 1, 2$$

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## Test case (2) - Regimes of dispersion



## Perspectives

- Accurate closure of the effective parameters
  - Numerical modeling at the local-scale (VOF)
- Impact of the coupled system on the dispersion?
- Closure of the liquid exchange term  $\dot{m}$ 
  - Numerical modeling at the micro-scale (quantification of the liquid exchange)

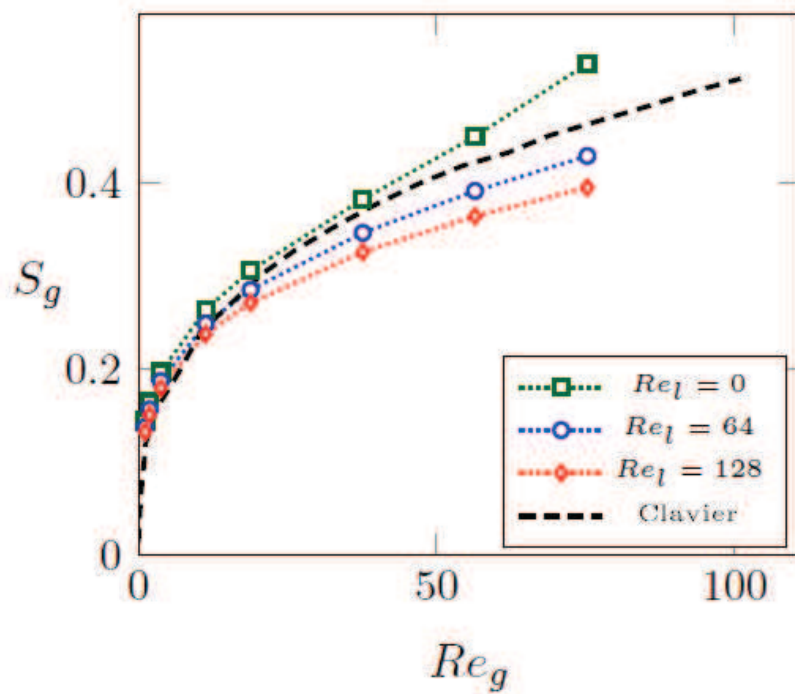
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## Annexe - Calide experiment - Retention



(a) Gas retention  $S_g$  as a function of the gas phase velocity



## Annexe - Calide experiment - Effective parameters

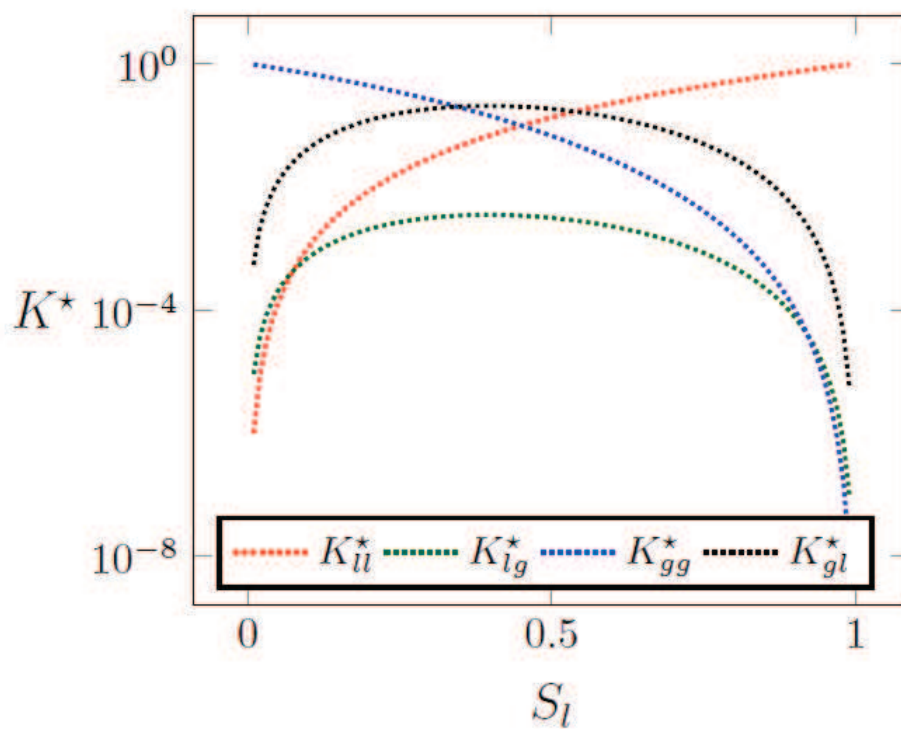
- Closures for the viscous terms - based on experimental results

$$K_{ll} = K_0 S_l^3 \quad ; \quad K_{lg} = 5.5 \frac{\mu_g}{\mu_l} \frac{S_l^2}{(1 - S_l)}$$
$$K_{gg} = K_0 (1 - S_l)^4 \quad ; \quad K_{gl} = \frac{\mu_l}{\mu_g} \frac{K_{gg} K_{lg}}{K_{ll}}$$

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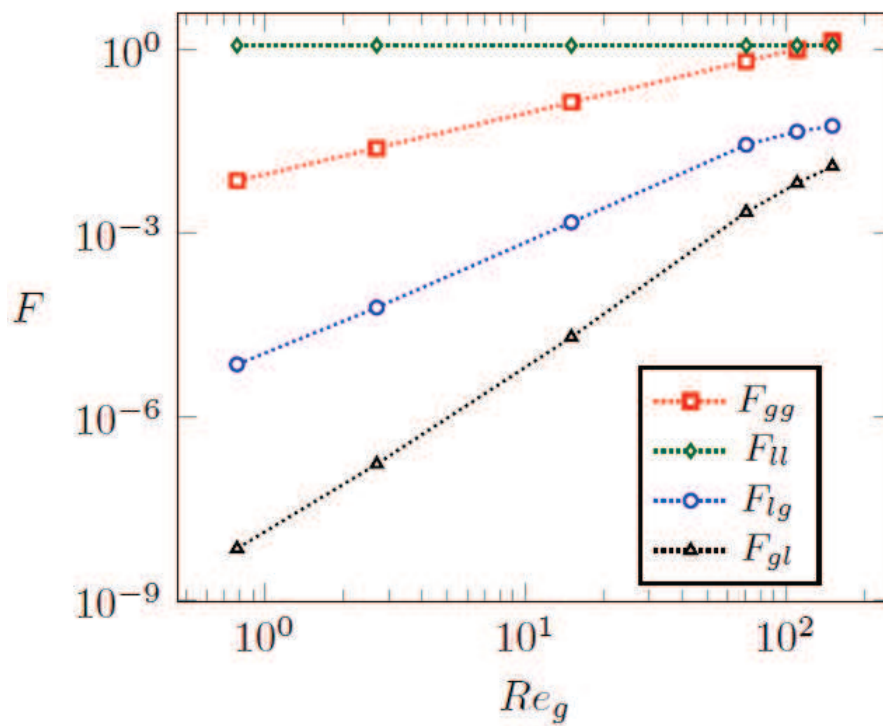
$$F_{ll} = \frac{\rho_l}{\mu_l} \frac{K}{\eta} \langle u_l \rangle \quad ; \quad F_{lg} = K_{lg} \frac{(1 - S_l)^3}{(1 - S_l)^3 + S_l^n}$$
$$F_{gg} = \frac{\rho_g}{\mu_g} \frac{K}{\eta} \langle u_g \rangle \quad ; \quad F_{gl} = f_{lg} (1 - S_l)^6$$

Annexe - Calide experiment - Effective parameters (1)



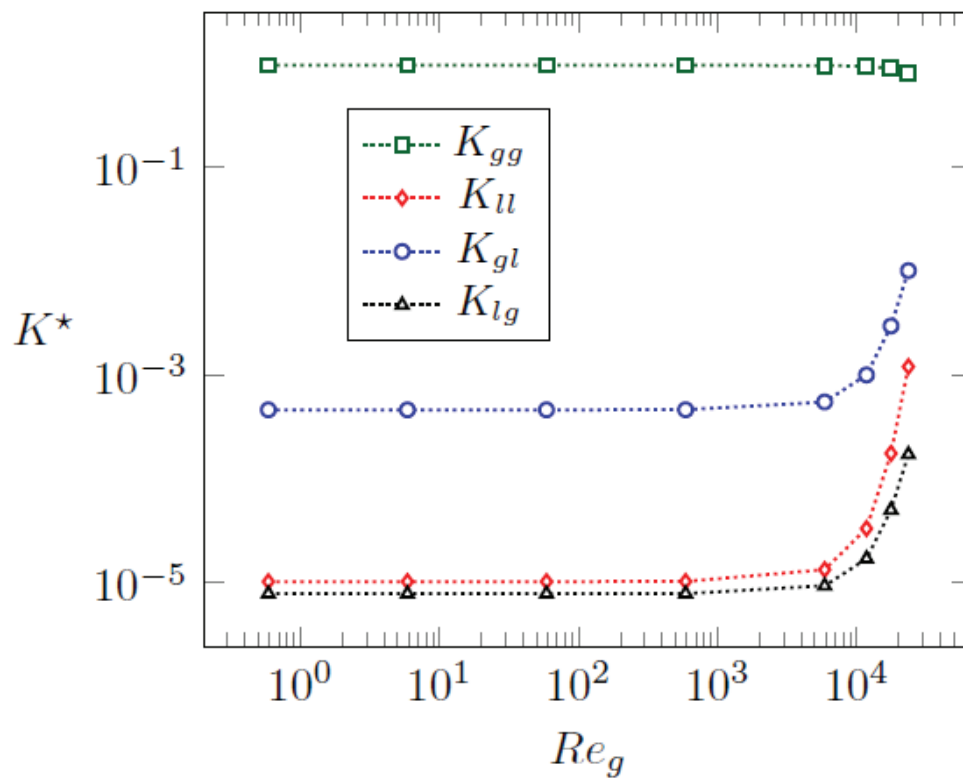
(a) Intrinsic and couples permeabilities - Experimental results (Clavier)

## Annexe - Calide experiment - Effective parameters (2)



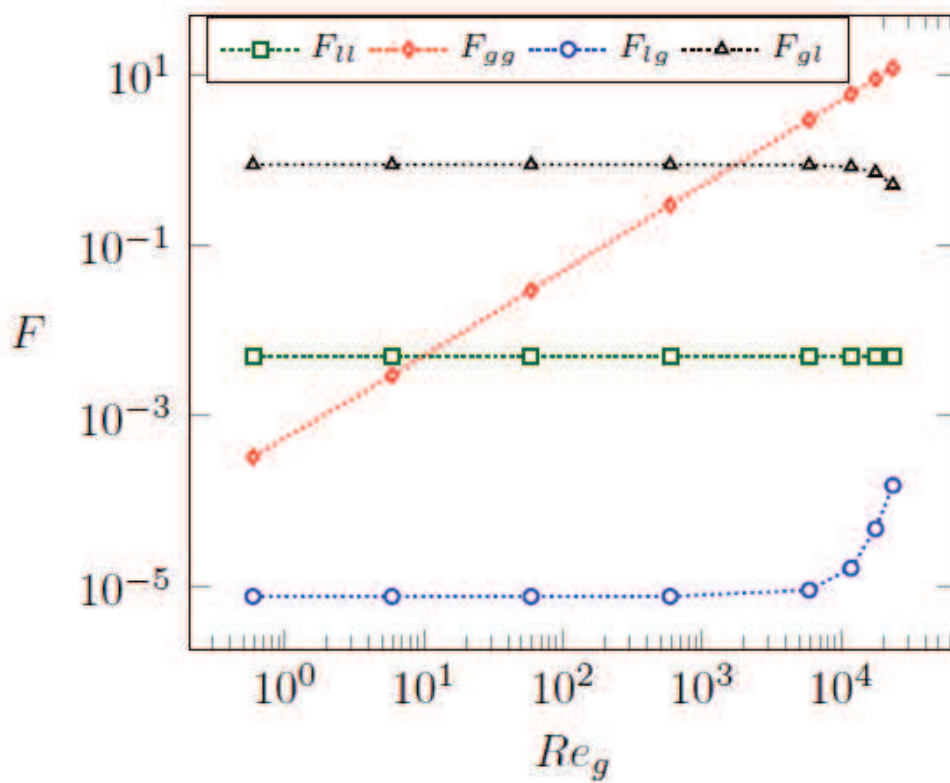
(b)  $\langle \mathbf{u}_l \rangle = 0.02$  ( $Re = 128$ )

## Annexe - air / water system in packings - Effective parameters (1)



(a) Viscous permeabilities  $K^*$

## Annexe - air / water system in packings - Effective parameters (2)



(b) Inertial correction terms  $F$