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# On the Understanding of the Macroscopic Inertial Effects in Porous Media

## Investigation of the Microscopic Flow Structure

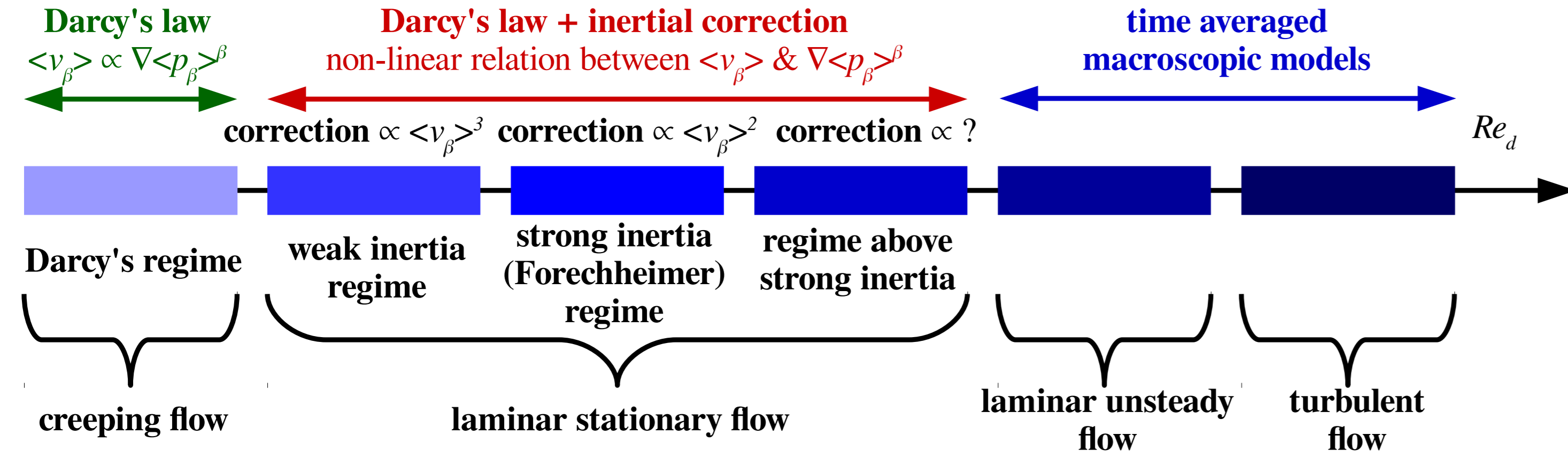
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### Abstract

Inertial flow in porous media occurs in many situations such as flow in column reactors, in filters or near wells for hydrocarbon recovery. It is characterized by a deviation from Darcy's law.

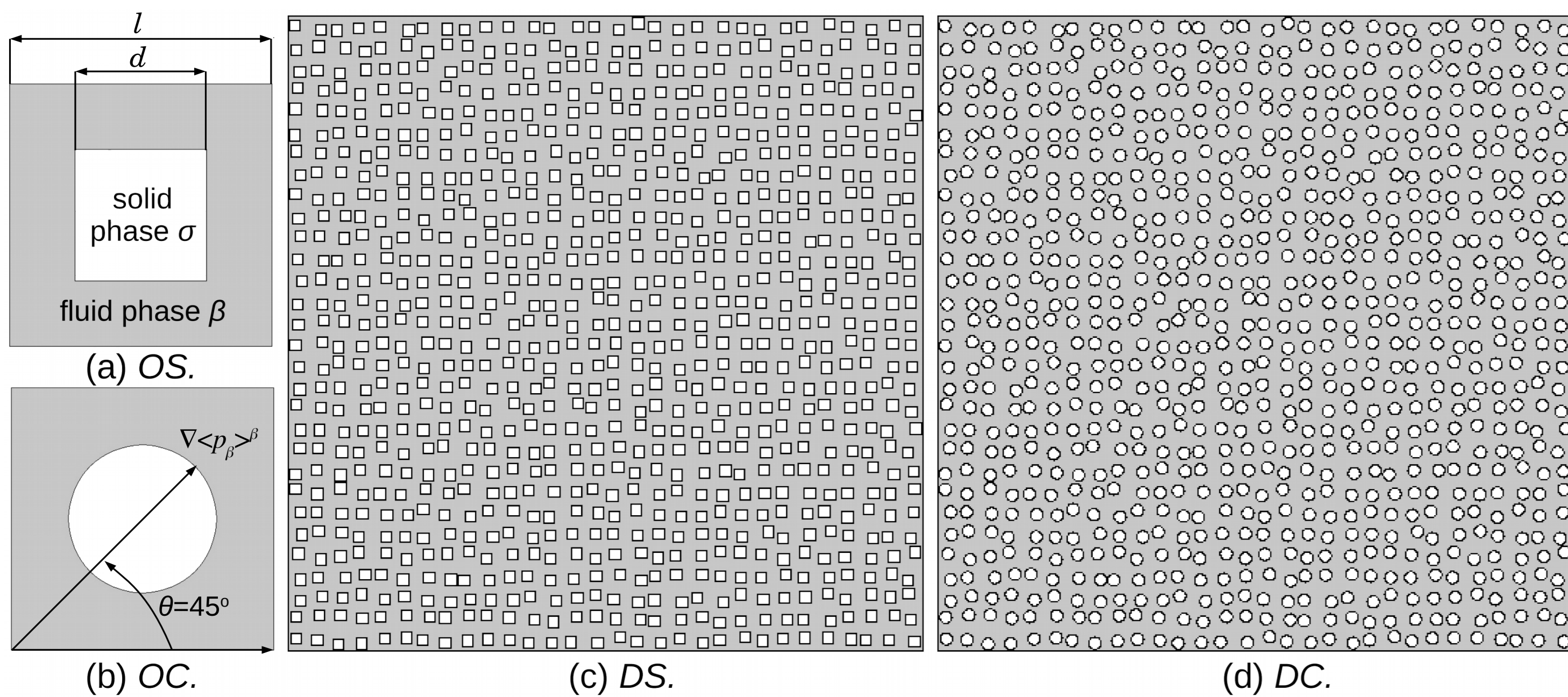


The existence and origin of different regimes, function of the microstructure and flow orientation, are still not well understood. We provide an in depth analysis of the flow structure to identify the origin of the deviation from Darcy's law using a theoretical justification. The role of the recirculation zones is highlighted.

### INTRODUCTION

#### Main Objectives

- Identify different inertial regimes with respect to:
  - the shape of the solid inclusions,
  - the structural disorder,
  - the orientation of  $\nabla \langle p_\beta \rangle^\beta$ .
- Identify the origin of the deviation from Darcy's law with respect to:
  - the role of the recirculation zones,
  - the flow structure to microscopic convective acceleration relationship.



- Ordered (a and b) / disordered (c and d) model structures of parallel cylinders. Porosity  $\epsilon = 75\%$ .
- Representative Elementary Volume (REV) made of  $1 \times 1$  (a and b) /  $30 \times 30$  (c and d) geometrical unit cells.

### Macroscopic Model & Determination of Macroscopic Coefficients

The macroscopic model was obtained from the volume averaging of the Navier-Stokes equations [3]

$$\langle \mathbf{v}_\beta^* \rangle = -\mathbf{K}^* \cdot \nabla \langle p_\beta^* \rangle^\beta - \mathbf{F} \cdot \langle \mathbf{v}_\beta^* \rangle = -\mathbf{H}^* \cdot \nabla \langle p_\beta^* \rangle^\beta \quad (1a)$$

$$\nabla \cdot \langle \mathbf{v}_\beta^* \rangle = 0 \quad (1b)$$

$\langle \mathbf{v}_\beta^* \rangle$ : filtration velocity.  $\nabla \langle p_\beta^* \rangle^\beta$ : macroscopic pressure gradient.  $\mathbf{K}^* = k^* \mathbf{I} = \mathbf{K}/l^2$ : intrinsic permeability tensor (structure dependent only).  $\mathbf{F}$ : inertial correction tensor.  $\mathbf{H}^* = (\mathbf{I} + \mathbf{F})^{-1} \mathbf{K}^* = \mathbf{H}/l^2$ : apparent permeability tensor.  $\mathbf{H}^*$  and  $\mathbf{F}$  depend on both the structure and the flow.

$\mathbf{K}^*$ ,  $\mathbf{H}^*$  and  $\mathbf{F}$  are determined from the solution of the closure problem on  $\mathbf{M}^*$  and  $\mathbf{m}^*$  that are periodic.

$$Re^* \nabla \langle p_\beta^* \rangle^\beta \cdot \mathbf{M}^{*T} \cdot \nabla \mathbf{M}^* = \nabla \mathbf{m}^* - \nabla^2 \mathbf{M}^* - \mathbf{I} \quad (2a)$$

$$\nabla \cdot \mathbf{M}^* = 0 \quad (2b)$$

$$\mathbf{M}^* = 0 \text{ at } A_{\beta\sigma} \quad (2c)$$

$$\langle \mathbf{M}^* \rangle = \mathbf{H}^* = \mathbf{H}/l^2 \quad (2d)$$

$$Re^* = \frac{\rho \beta^3}{\mu_\beta^2} |\nabla \langle p_\beta^* \rangle^\beta|: \text{ Reynolds number (define the}$$

forcing intensity).  $\nabla \langle p_\beta^* \rangle^\beta$ : unit vector (define the macroscopic flow orientation  $\theta$ ). As in [2], the deviation from Darcy's law was analyzed in terms of the inertial correction vector

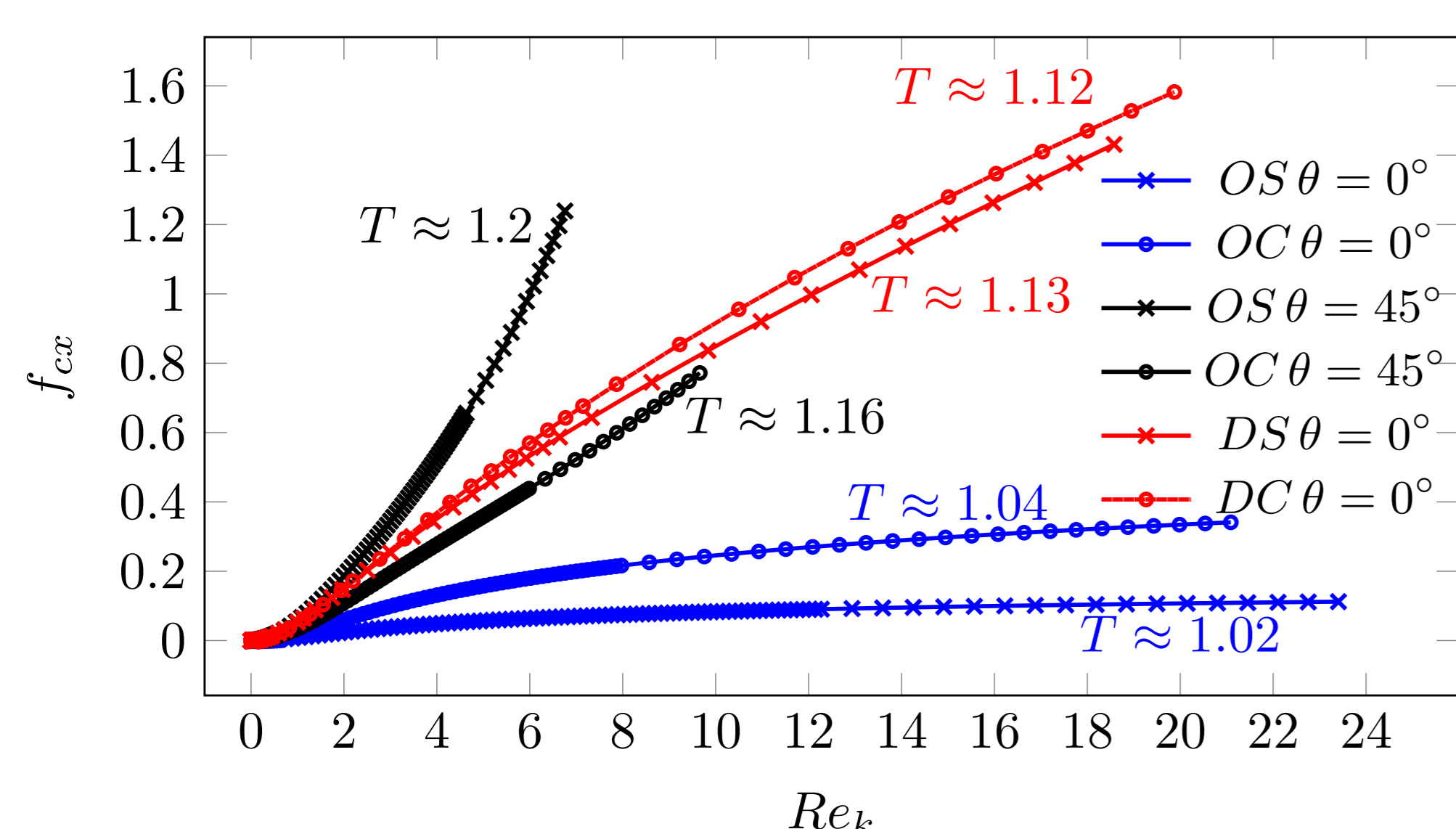
$$\mathbf{f}_c = -\mathbf{F} \cdot \langle \mathbf{v}_\beta^* \rangle / |\langle \mathbf{v}_\beta^* \rangle| \quad (3)$$

and with respect to the Reynolds number

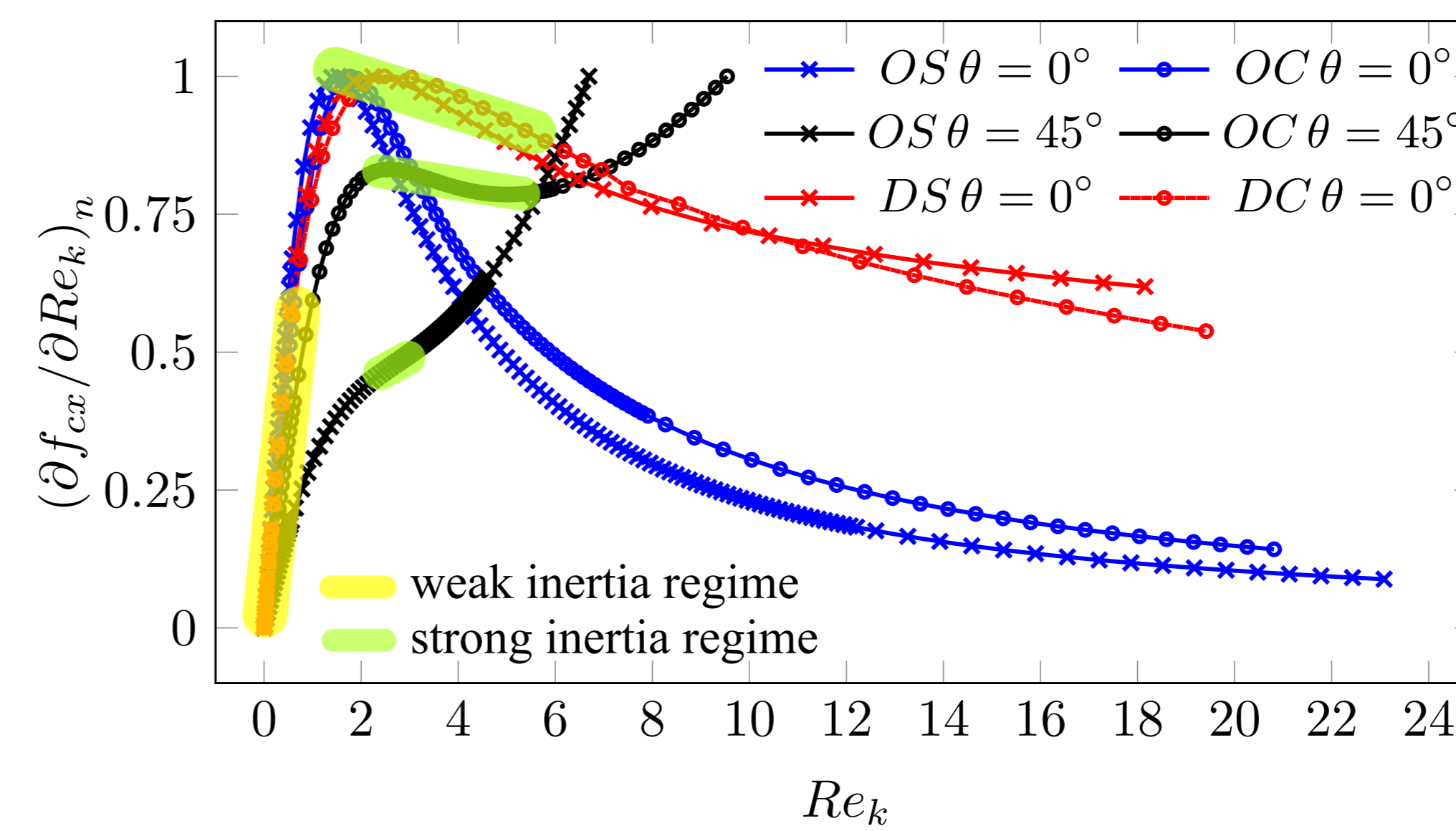
$$Re_k = |\langle \mathbf{v}_\beta^* \rangle| \sqrt{k^*} Re^* = \frac{\sqrt{k^*}}{d^*} Re_d \quad (4)$$

### RESULTS

#### Inertial Correction

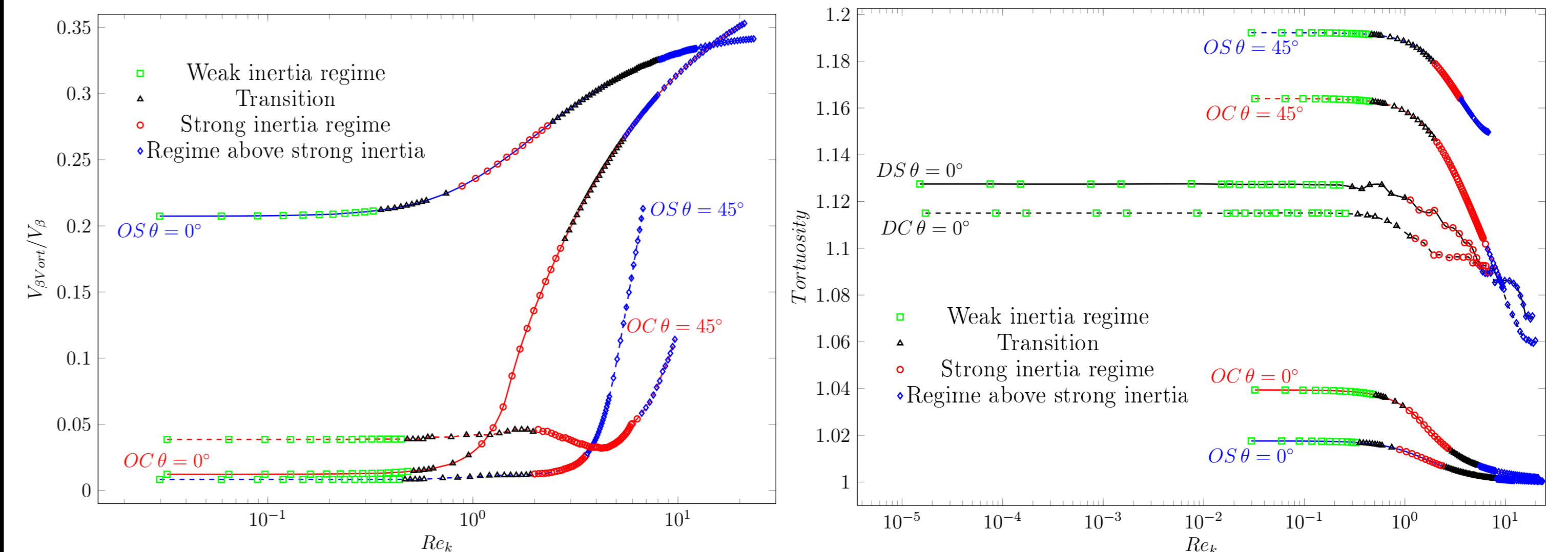


- Intensity of inertial effects depend on the microstructure & orientation of  $\nabla \langle p_\beta^* \rangle^\beta$  as observed before [2].
- Inertial effects increase with tortuosity  $T$ .
- Contribution of structural disorder to inertial effects is larger than that due to the solid inclusions shape.

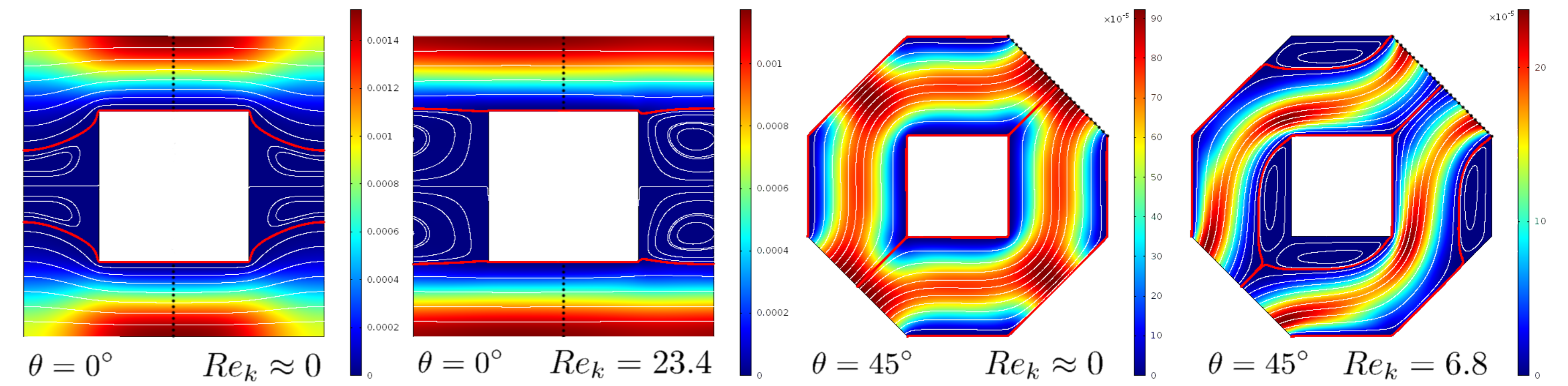


- Weak inertia regime ( $f_{cx} \propto Re_k^2$ ), is identified in all configurations over almost the same  $Re_k$  interval except on the disordered structures where it is shorter.
- Strong inertia ( $f_{cx} \propto Re_k$ ) depends on the microstructure and orientation of  $\nabla \langle p_\beta^* \rangle^\beta$  but is more robust in the presence of structural disorder.
- A regime above strong inertia is observed over large  $Re_k$  intervals.

### Role of the Recirculation Zones



- Kinetic energy lost in vortices is negligible as it is always  $< 0.5\%$  of the total kinetic energy.
- Volume of recirculation zones ( $V_{\beta Vort}$ ) is important & its variation with  $Re_k$  leads to streamlines deformation.
- Enlargement of recirculation zones beyond weak inertia regime decreases tortuosity (with different rates).

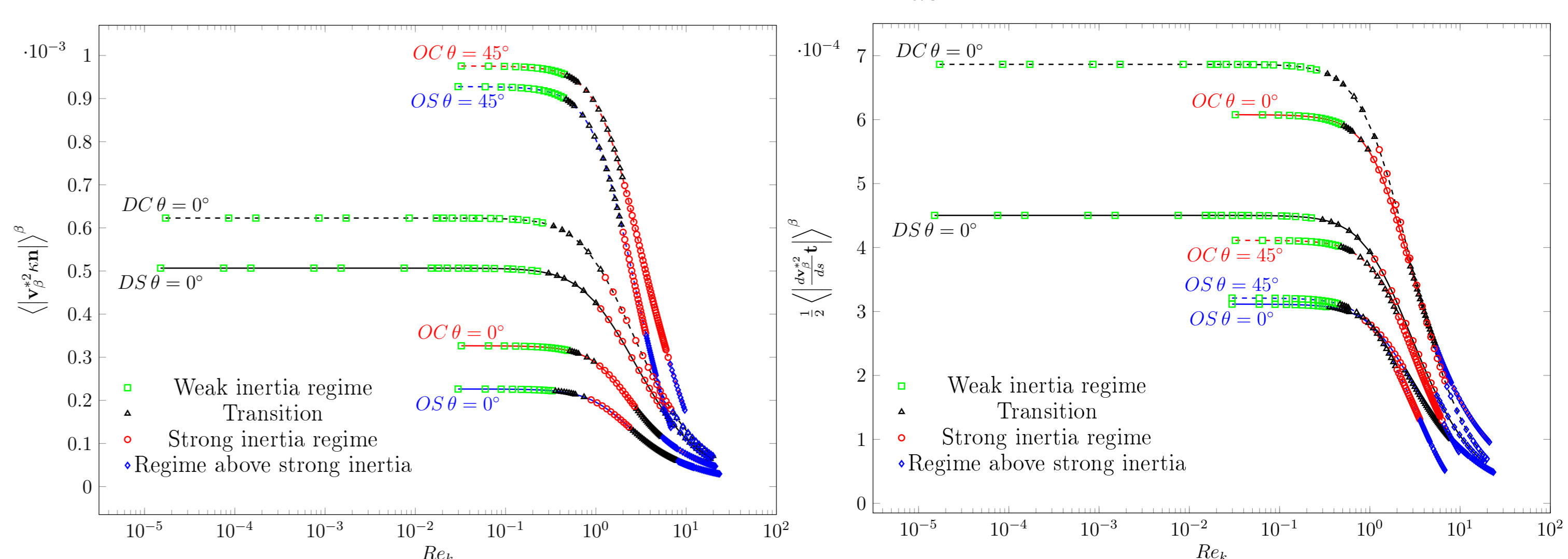


- Flow structure in OS. Recirculation zones delimited by red streamlines enlarge with  $Re_k$ .

### Relation between Convective Term & Flow Structure

Decomposition of the convective acceleration in the orthonormal basis ( $\mathbf{t}$ ,  $\mathbf{n}$ ) of the Frenet frame:

$$(\mathbf{v}_\beta^* \cdot \nabla) \mathbf{v}_\beta^* = \mathbf{v}_\beta^{*2} \kappa \mathbf{n} + \frac{1}{2} \frac{d\mathbf{v}_\beta^{*2}}{ds} \mathbf{t} \quad (5)$$



- Whereas the 1st term of the RHS of Eq. 5 corresponds to streamlines curvature ( $\kappa$ ) weighted by the local kinetic energy, the 2nd characterizes the variation of kinetic energy along the streamlines. The 1st term can be related to tortuosity, invoked heuristically in the literature.
- Constant flow structure on weak inertia regime resembling that of creeping flow is observed.
- Beyond weak inertia, different variations occur explaining the various behaviors of the inertial correction.

### CONCLUSIONS

- As in [2],
  - weak inertia regime is always well identified,
  - strong inertia regime is robust in the presence of structural disorder yielding a shorter weak inertia regime and stronger inertial effects.
- The kinetic energy lost in vortices is insignificant.
- Streamlines shape induced by the recirculation zones implies variations in the flow structure which is itself correlated to the flow regimes.
- The intensity of inertial effects and the occurrence

of different inertial regimes is correlated to the flow structure based on a formal justification.

- The higher the tortuosity, the stronger inertial effects.
- The weak inertia regime is characterized by a constant flow structure.
- Beyond weak inertia, different and complex flow structure variations occur explaining the weakness of the Forchheimer model.

More details about this work can be found in [1].

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