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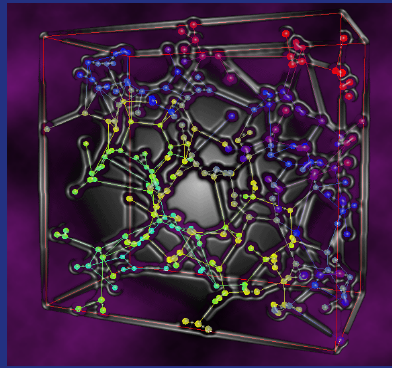
UMR 7343

Aix*Marseille université

POLYTECH MARSEILLE

UNE GRANDE ÉCOLE D'INGÉNIEURS AU CŒUR DE L'UNIVERSITÉ

MILIEUX CELLULAIRES OUVERTS : STRUCTURE ET PROPRIETES DE TRANSPORT



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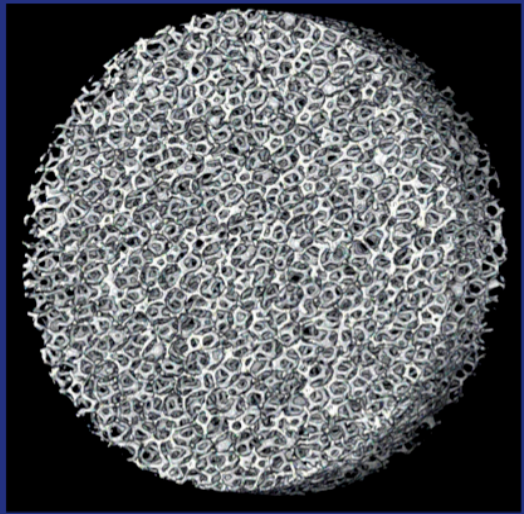

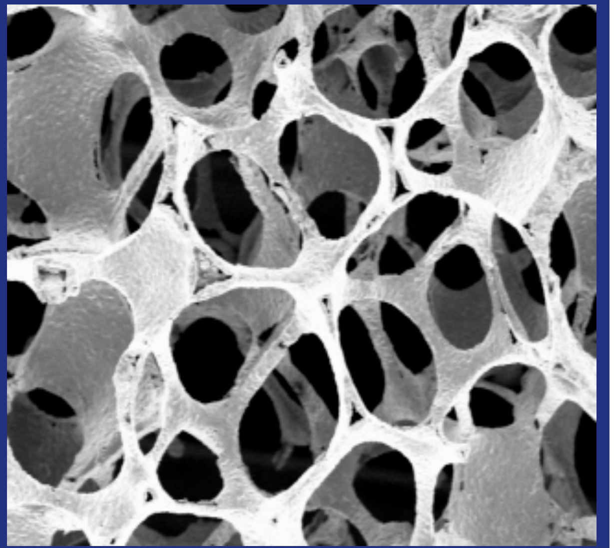

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Contexte

•Compréhension des transferts de chaleur et de masse dans les poreux
•Impact de la structure sur les propriétés thermophysiques et d'écoulement

Expériences :

Configuration simplifiée

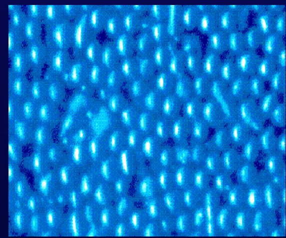
Conditions contrôlées

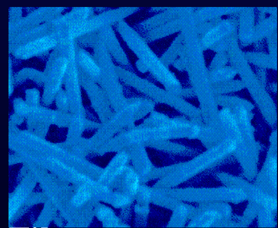
Structures modèles/Milieux réels

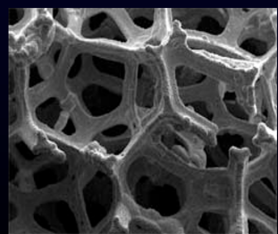
Modèles :

Physique à l’échelle du pore

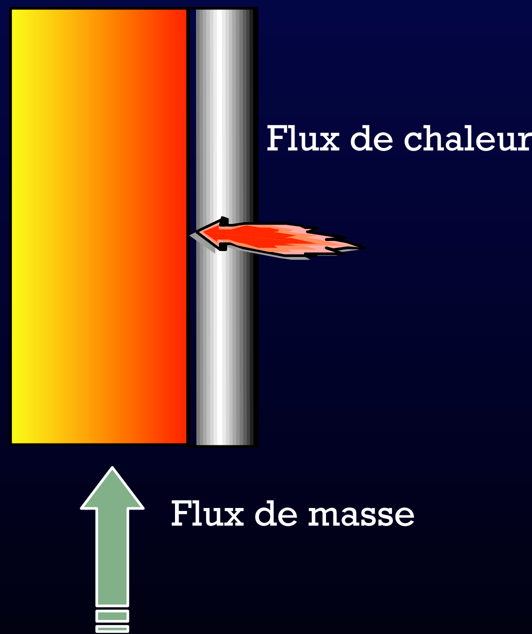
Couplages à l’échelle de l’échantillon


Lits de billes


Fibreux


Mousses solides

Modèles physique



Propriétés

- Multiplicités des paramètres

- Géométriques

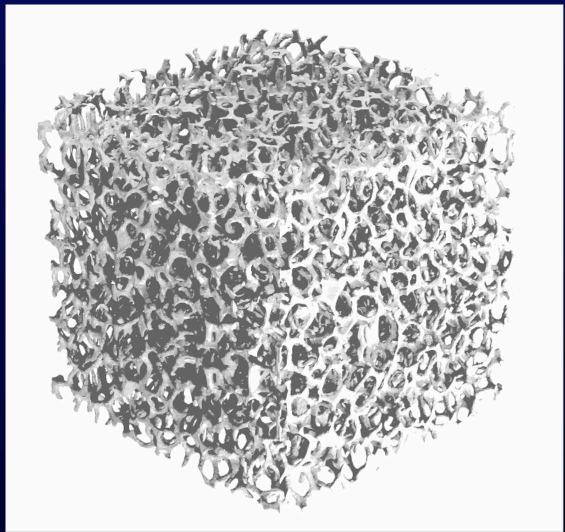
- Thermophysiques (conductivité, dispersion, coefficient d'échange)
- Lois d'écoulement (perméabilité, coefficient inertiel)
- Ecoulement polyphasiques (Modèles homogènes, à phases séparées)
- mouillabilité, pression capillaire ....
- Ebullition (courbe d'ébullition, CHF,....)

- Mécaniques

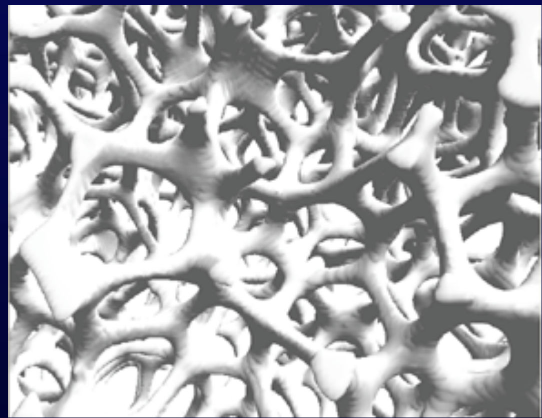
- Chimiques

Quelques exemples de mousses

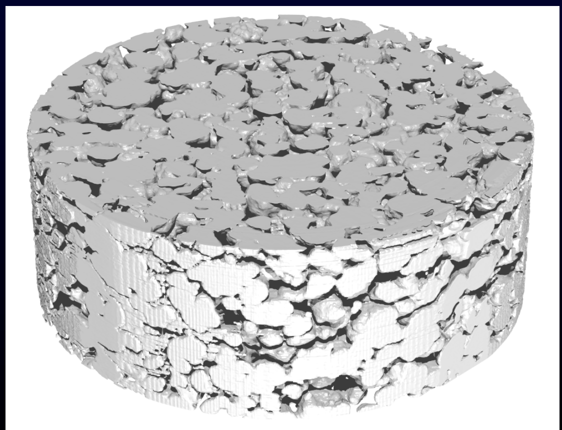
NiCr foams – Recemat
(10,20,30,40,50,100 ppi)



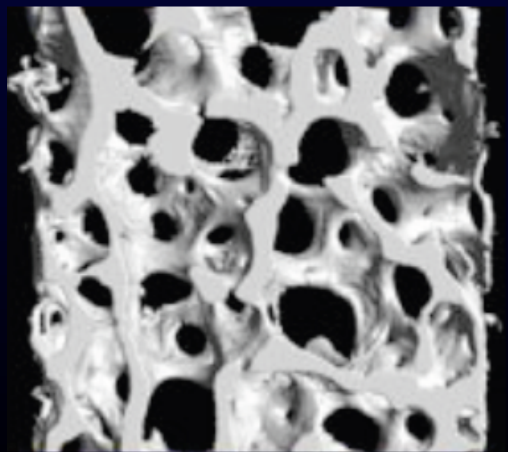
Al foams – ERG (5,10,20 ppi)



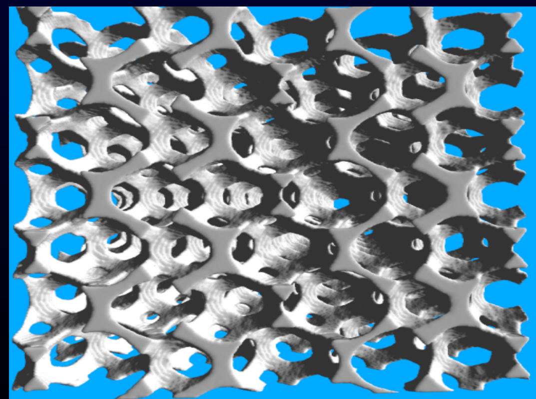
Ceramic foams



Sintered Polyethylene - Porvair

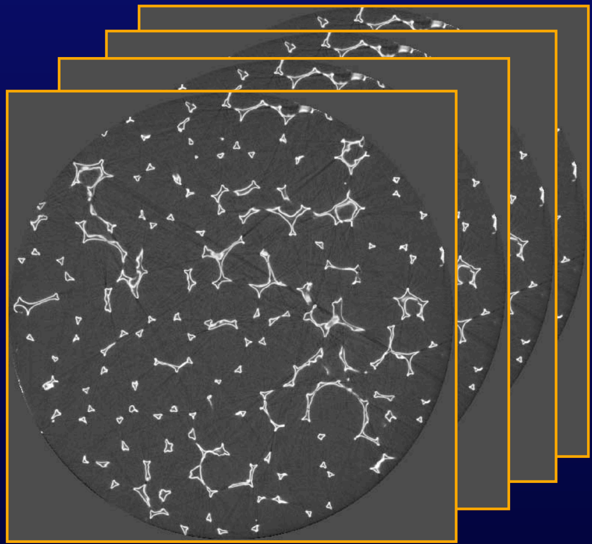


Trabecular bone



Kelvin cell -CTIF

iMorph : Fonctionalités

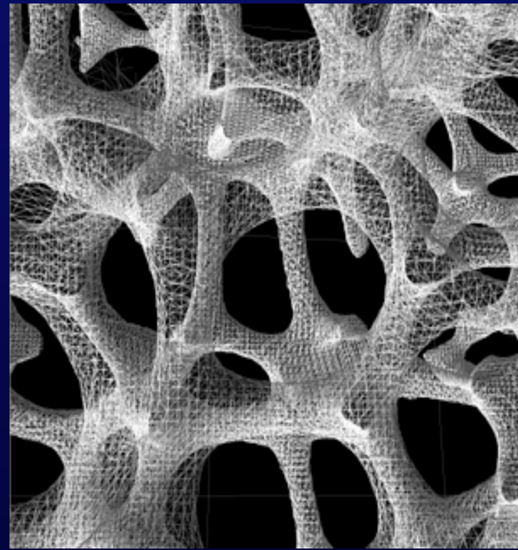


Segmentation des phases:
solide/ fluide

Reconstruction 3D

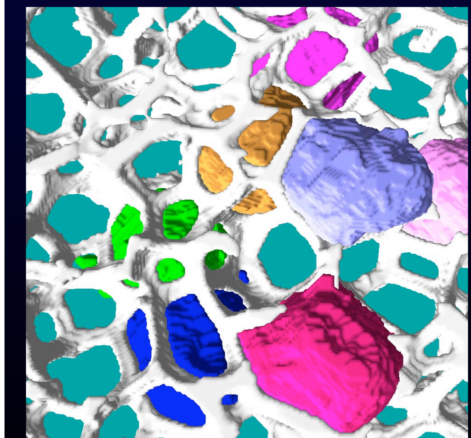
Tesselation de l' interface

Visualisation
Porosité
Surface spécifique
Exportation vers les codes CFD



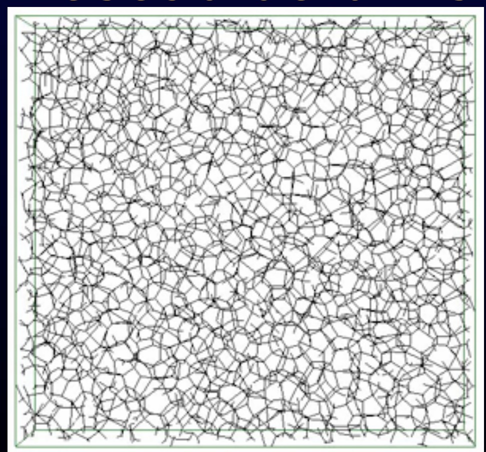
Extraction des éléments structurants

Cellules



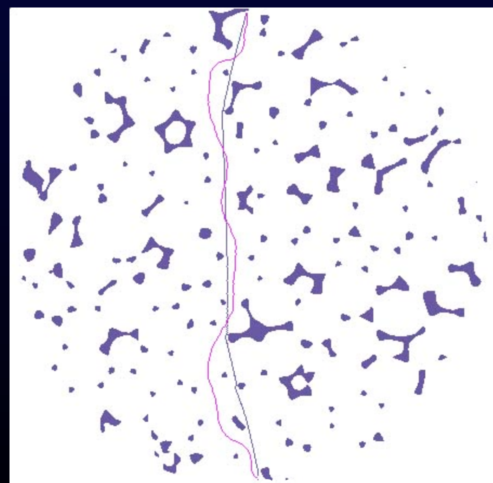
Porosimetrie
Forme des pores
Orientations

Réseau de brins



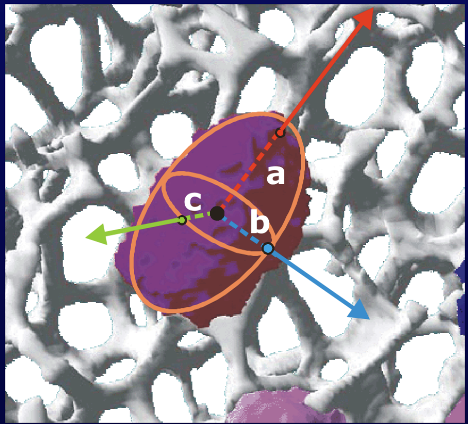
Orientations
Connectivité
Longueurs

Calculs Géodésiques



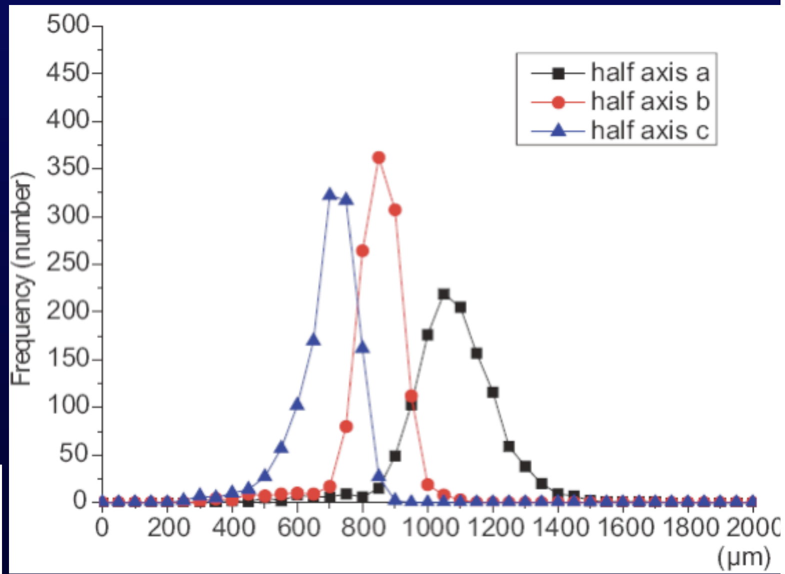
Plus courts chemins
Tortuosité

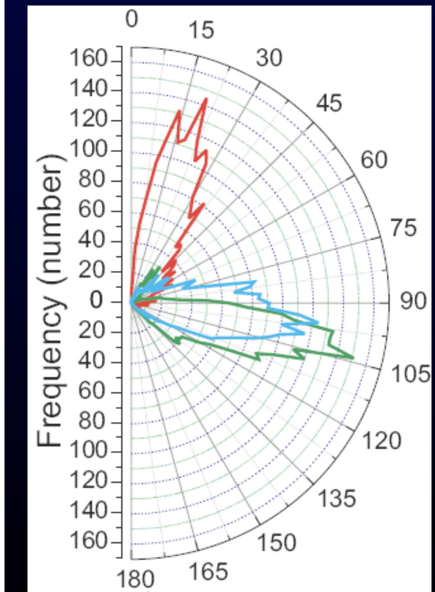
Forme et orientation des cellules



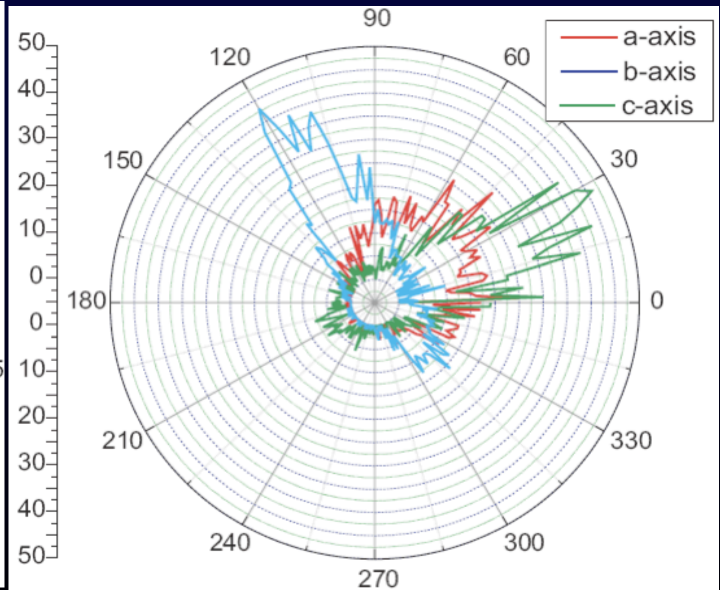
Mesure des ellipsoïdes équivalents
(Matrice d’inertie du nuage de voxels)

Distribution des longueurs de demi-axes





Elevation

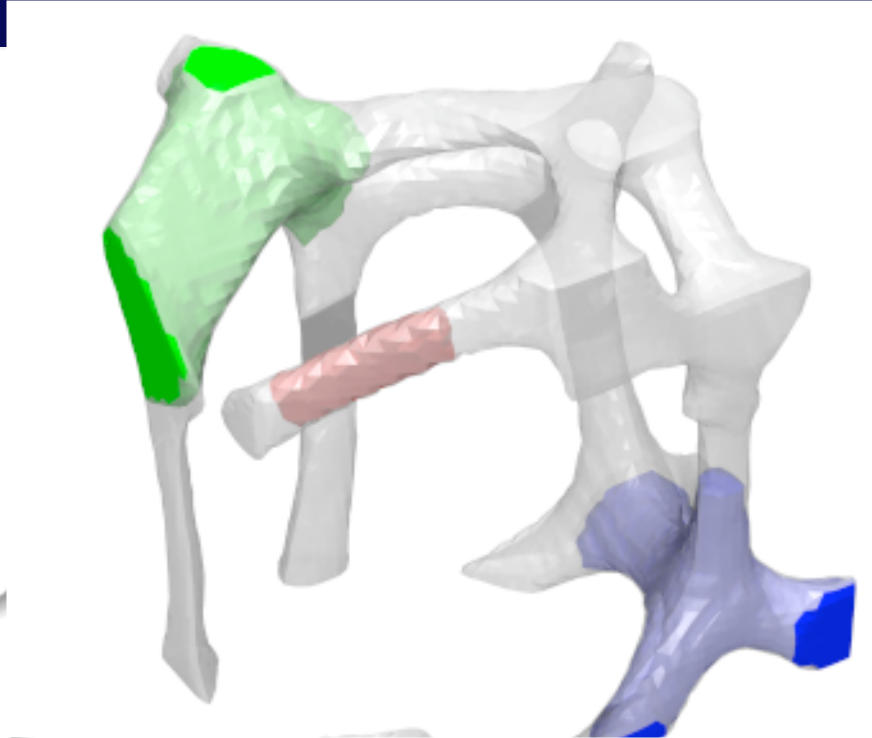


Azimuth

Cellules orientés de manière identique dans l’espace

Organisation → Anisotropie de l’espace poral

Classification locale de formes

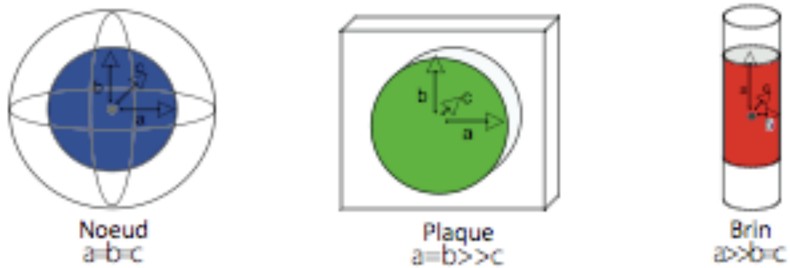


Analyse classique

- Dans la littérature le point de départ est l'obtention de squelettes
- Squelette filaire pas toujours représentatif (pyramide, plaque)

Identification des formes locales

- Identifier les voxels connexes à une certaine distance géodésique (Fast Marching)
- Matrice d'inertie du nuage de voxel obtenu
- Classification en objets élémentaires grâce aux moments d'inertie



En Bref

- Cells present ellipsoid shape
- Cells organization induces anisotropy
- Geometrical tortuosity depends on orientation and organisation
- Foams are homothetic

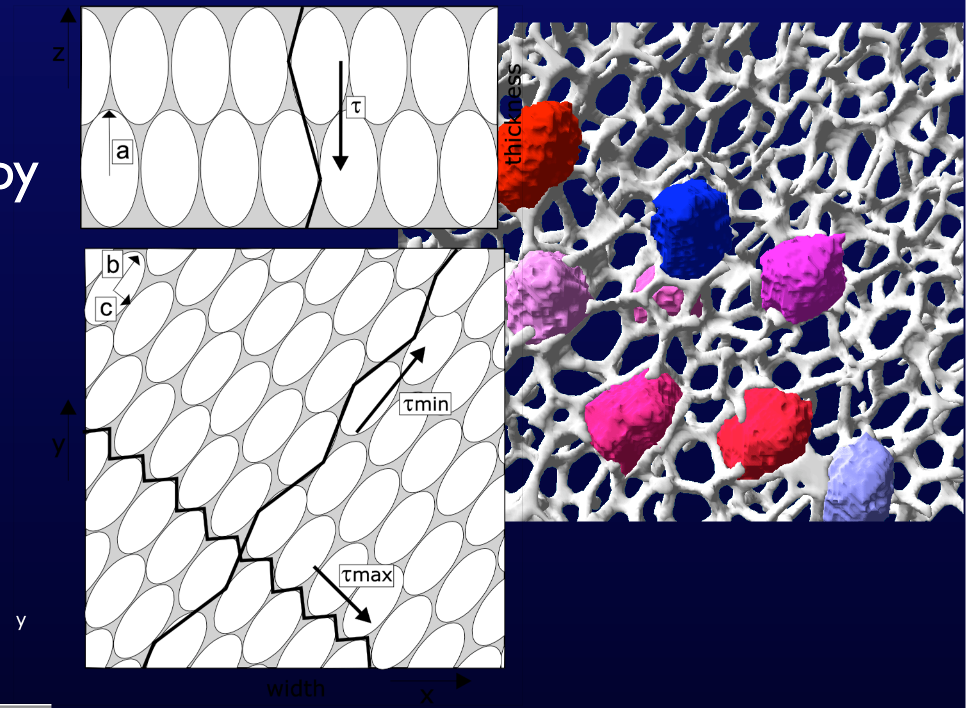


TABLE 1. Presentation of geometrical parameters

Samples	ε	Sp.Surface (m^2/m^3)	d_s (mm)	d_l (mm)	dp* (mm)
1	0.825	370.9	1.9	3.6	8.7
2	0.84	357.4	1.9	3.6	8.7
3	0.845	263.9	2.5	5.0	12.4
4	0.85	252.2	2.5	5.0	12.7

d_p*- calculated for equivalent included spherical diameter

Structural dependencies

Sp = 3/dPore

dThroat = 0.52 dPore

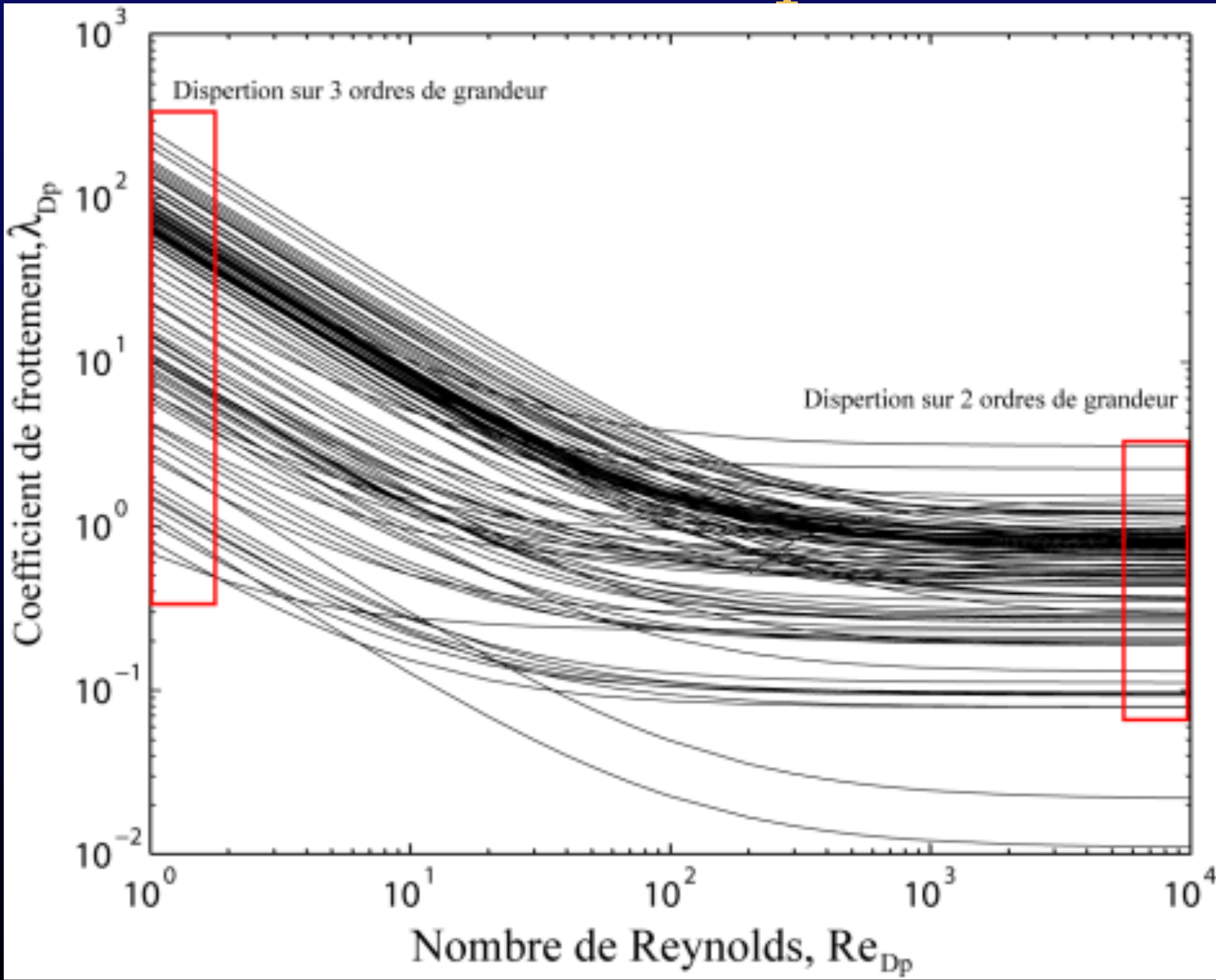
Strut length = 0.4 dPore

What is known ?

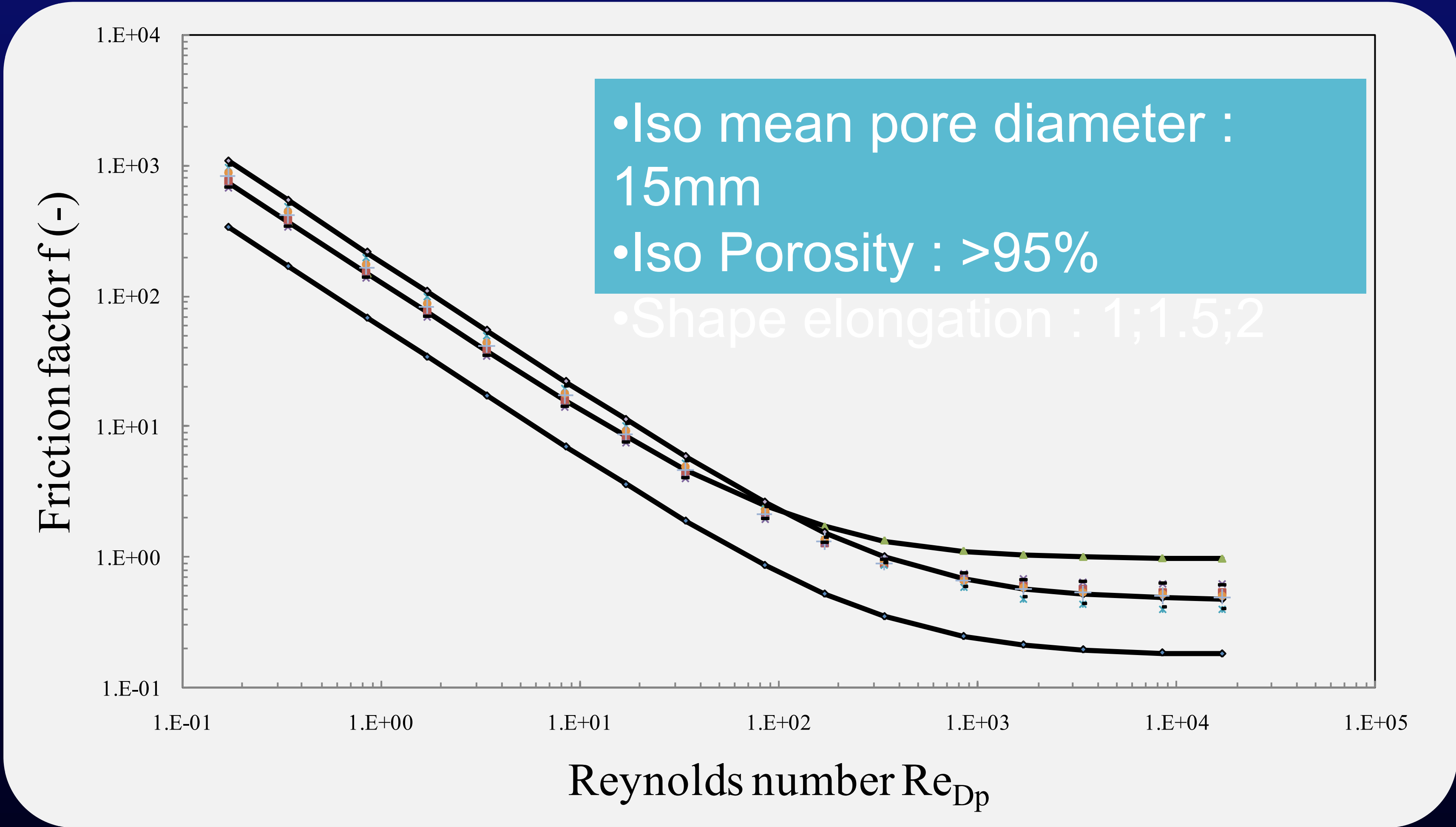
- Effective conductivity l depends on porosity e and on tortuosity t
- l independent from D_p
  - ➔ Pore shape depend on pore size

- Permeability K and Inertia coefficient b depend on D_p :
  $K \sim D_p^2$ & $b \sim D_p^{-1}$
- And other parameters ...

Problematique écoulement



Dispersion des résultats



•Ergun like approach not adapted to describe flow law in foam

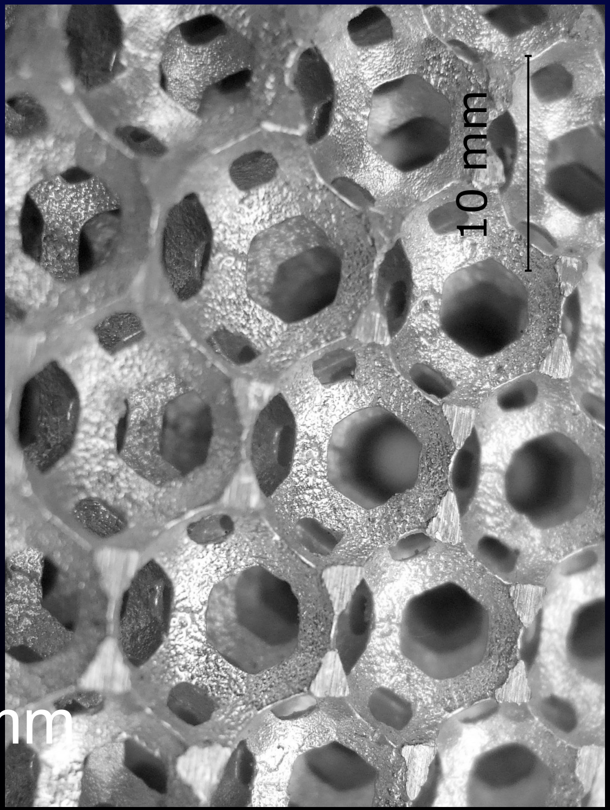
➔Develop a model more accurate for foam

➔Study influence of pore shape on properties

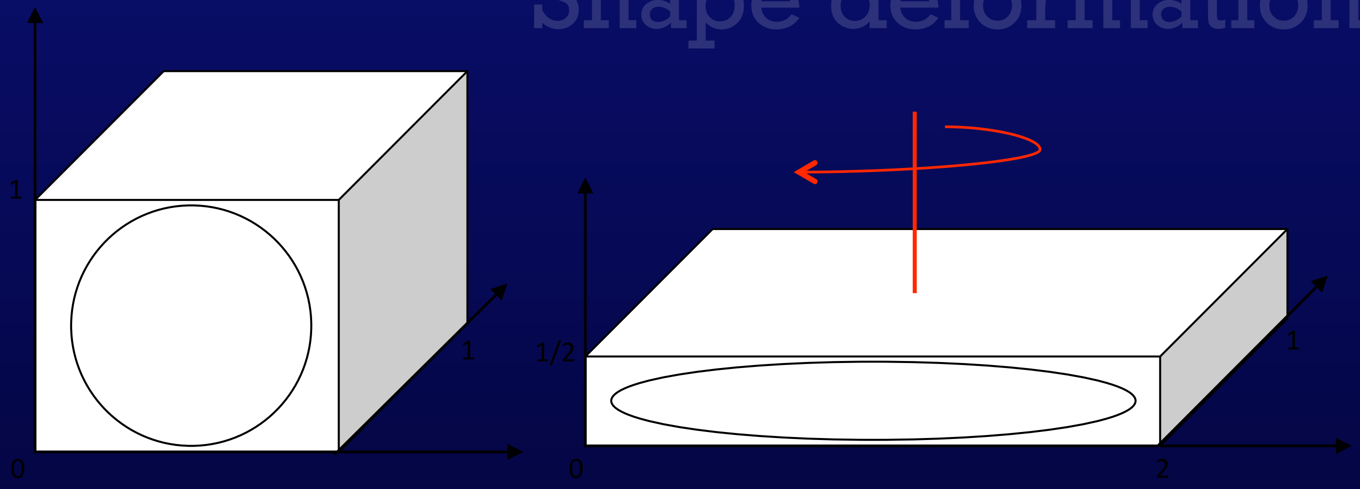
Kelvin's cell

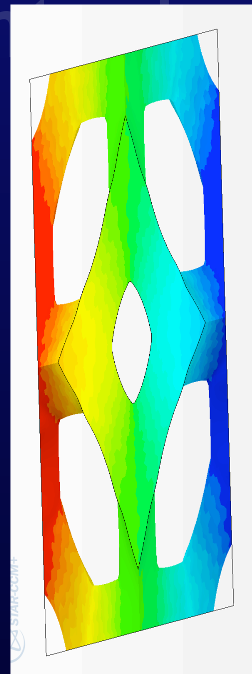
- Tetrakaleidon (14 faces)
- One of models that well describe metal foams
- Widely used
- Casted samples are available and characterized
- Periodic structure
- Isotropic material
- Both CAD and Tomography available

e=87%
D_p=14.2mm
…



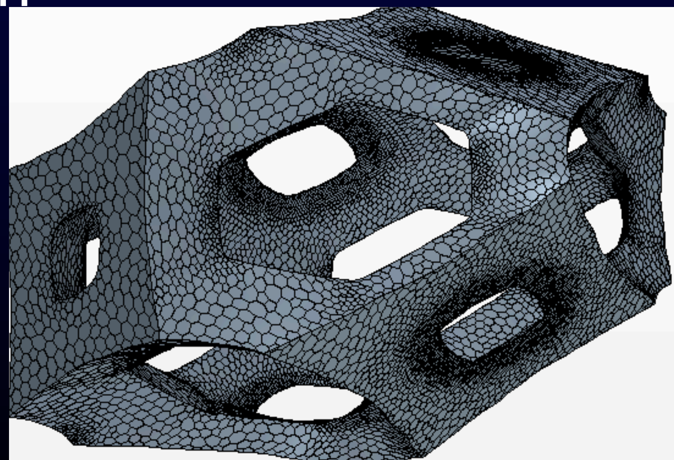
Shape deformation con





Stretching and shearing

Scaling factor a in x direction ; 1/sqrt(a) in Y and Z direction



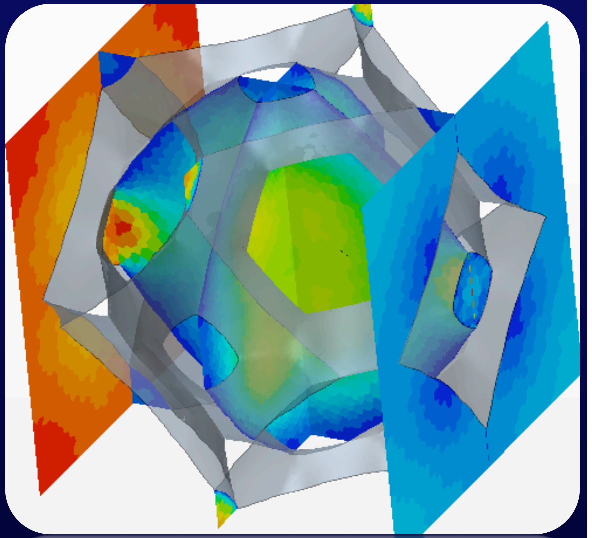
Rotation around Z axis

0.4 < a < 4.0 and 0 < q < 45°

20x45 Virtual samples produced

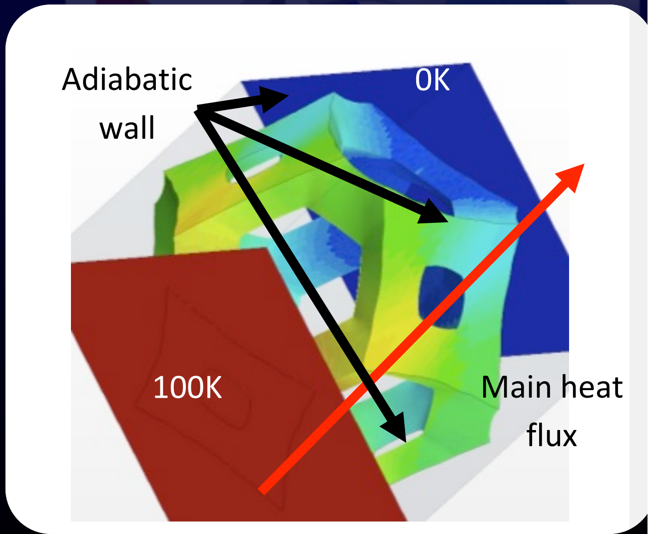
Porosity, pore equivalent volume sphere diameter are conserved

Pore scale numerical simulation

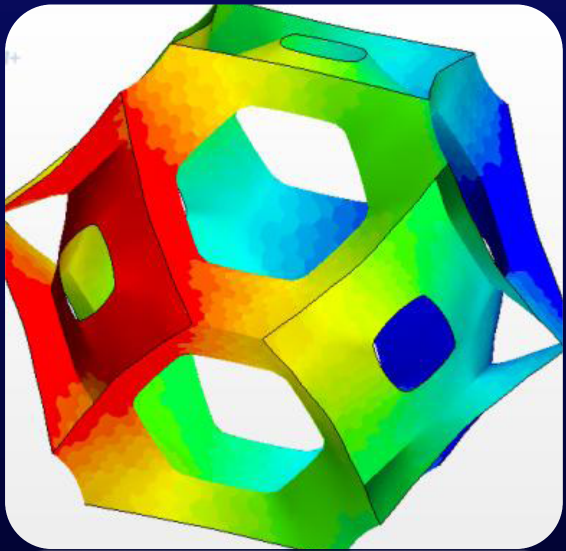


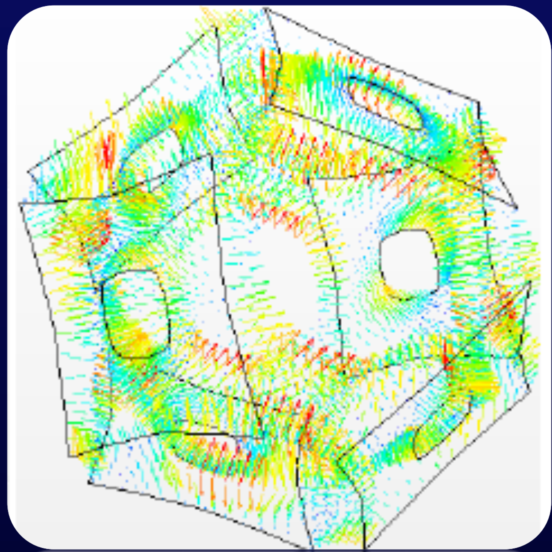
- Mesh size : Polyhedral cell core + prism layers near the solid matrix surface
    - About 400.000 cells
- Fluid phase conductivity is equal to 10W/mK , 100W/mK for solid phase
- Navier-Stokes and energy balance equations are solved in steady condition

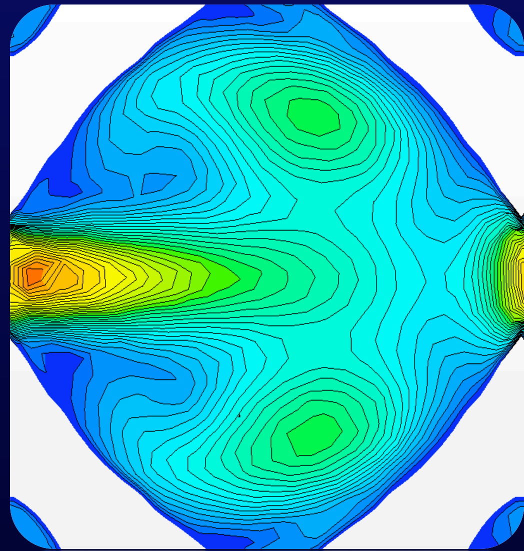
- Boundary conditions :
- permeameter conditions (flux in one direction, no flux on other face):
    - Temperature difference imposed on two opposite faces, adiabatic on other face
    - Pressure difference imposed on two opposite faces, slip condition on other faces



Volume averaging technique







$$\vec{\varphi} = \overline{\overline{K_{eff}}}.\nabla < T >$$

Similar correlation for Darcy'law

$$\nabla < T_x > = \frac{1}{V}\int_V .\overrightarrow{\nabla T(x)}.\ \vec{n_x}.dV$$

Simplification

$$\nabla T_x = \frac{1}{V}\int_S T(x).\vec{\iota}.\ \vec{n_x}.dS = \frac{\Delta < T_x >}{\Delta x}$$

$$\varphi_x = \frac{1}{V}\int_S x.\overrightarrow{\varphi(x)}.\ \vec{n_x}.dS = \frac{P_x}{S_x}$$

Full tensors determination

•Samples are anisotropic ➔ thermo-physical parameters are tensors

$$\overline{\overline{K_{eff}}} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$$

•Tensors are positive and symmetric :

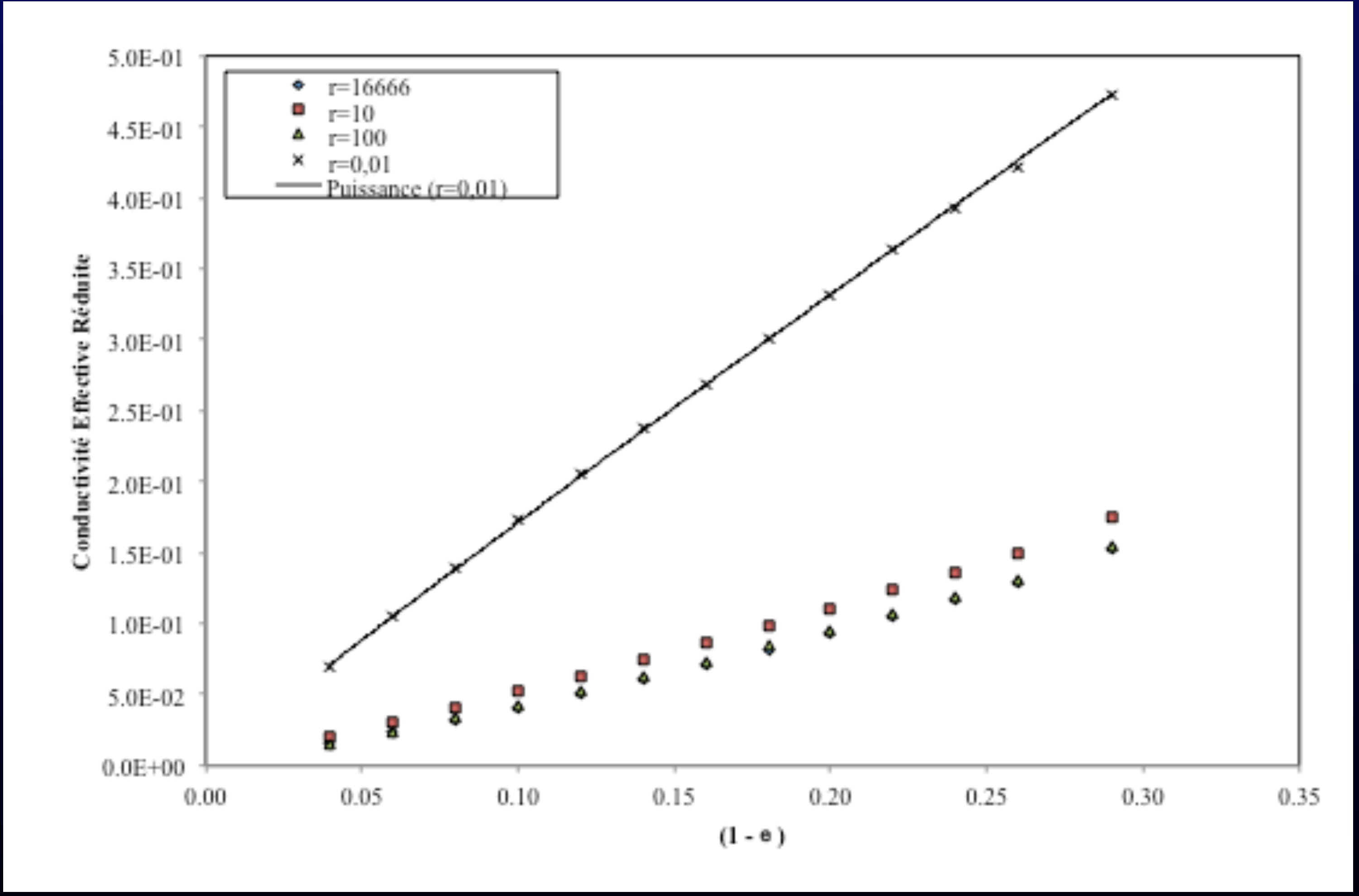
•Experiment is repeated in each direction X, Y and Z

•9 equa… by least square…

$$\begin{bmatrix} K_{xx} \\ K_{xy} \\ K_{xz} \\ K_{yx} \\ K_{yy} \\ K_{yz} \\ K_{zx} \\ K_{zy} \\ K_{zz} \end{bmatrix} = \begin{bmatrix} \nabla T_x^1 & \nabla T_y^1 & \nabla T_z^1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \nabla T_x^1 & \nabla T_y^1 & \nabla T_z^1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \nabla T_x^1 & \nabla T_y^1 & \nabla T_z^1 \\ \nabla T_x^2 & \nabla T_y^2 & \nabla T_z^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \nabla T_x^2 & \nabla T_y^2 & \nabla T_z^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \nabla T_x^2 & \nabla T_y^2 & \nabla T_z^2 \\ \nabla T_x^3 & \nabla T_y^3 & \nabla T_z^3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \nabla T_x^3 & \nabla T_y^3 & \nabla T_z^3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \nabla T_x^3 & \nabla T_y^3 & \nabla T_z^3 \end{bmatrix}^{-1} \begin{bmatrix} \varphi_x^1 \\ \varphi_y^1 \\ \varphi_z^1 \\ \varphi_x^2 \\ \varphi_y^2 \\ \varphi_z^2 \\ \varphi_x^3 \\ \varphi_y^3 \\ \varphi_z^3 \end{bmatrix}$$

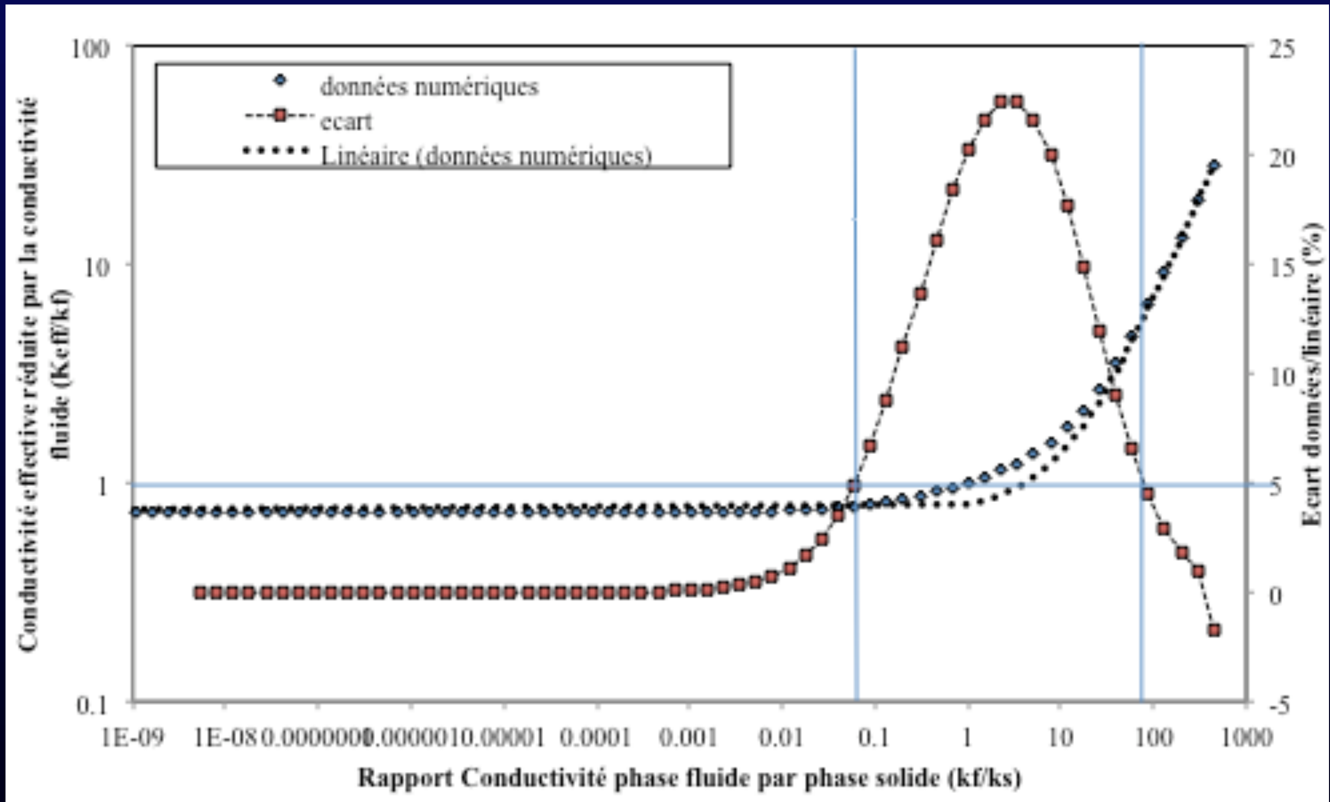
Results

Conductivité effective réduites des cellules de Kelvin en fonction de la porosité



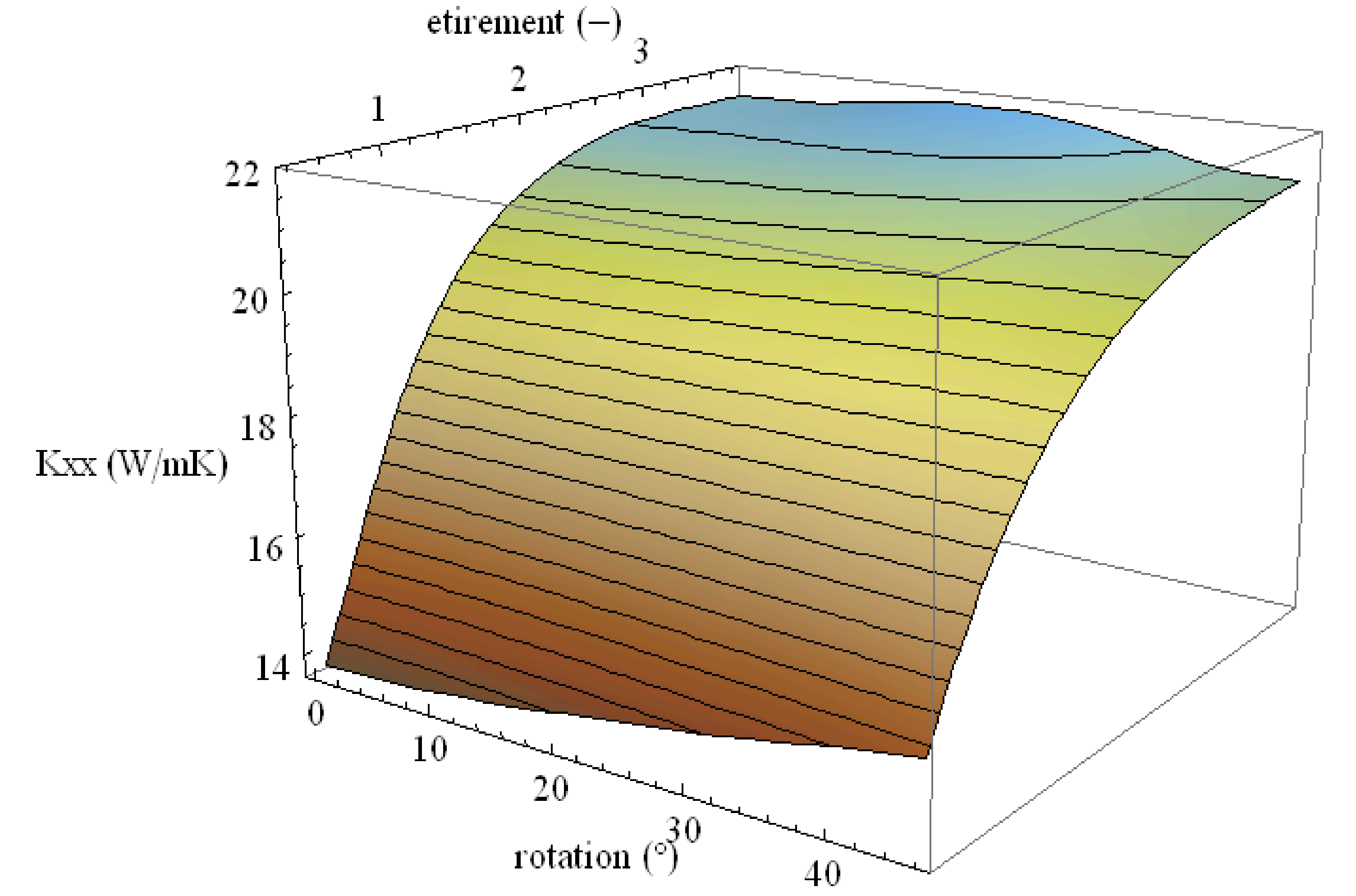
pour 4 rapports de conductivité fluide/solide r

Effet du rapport de conductivité

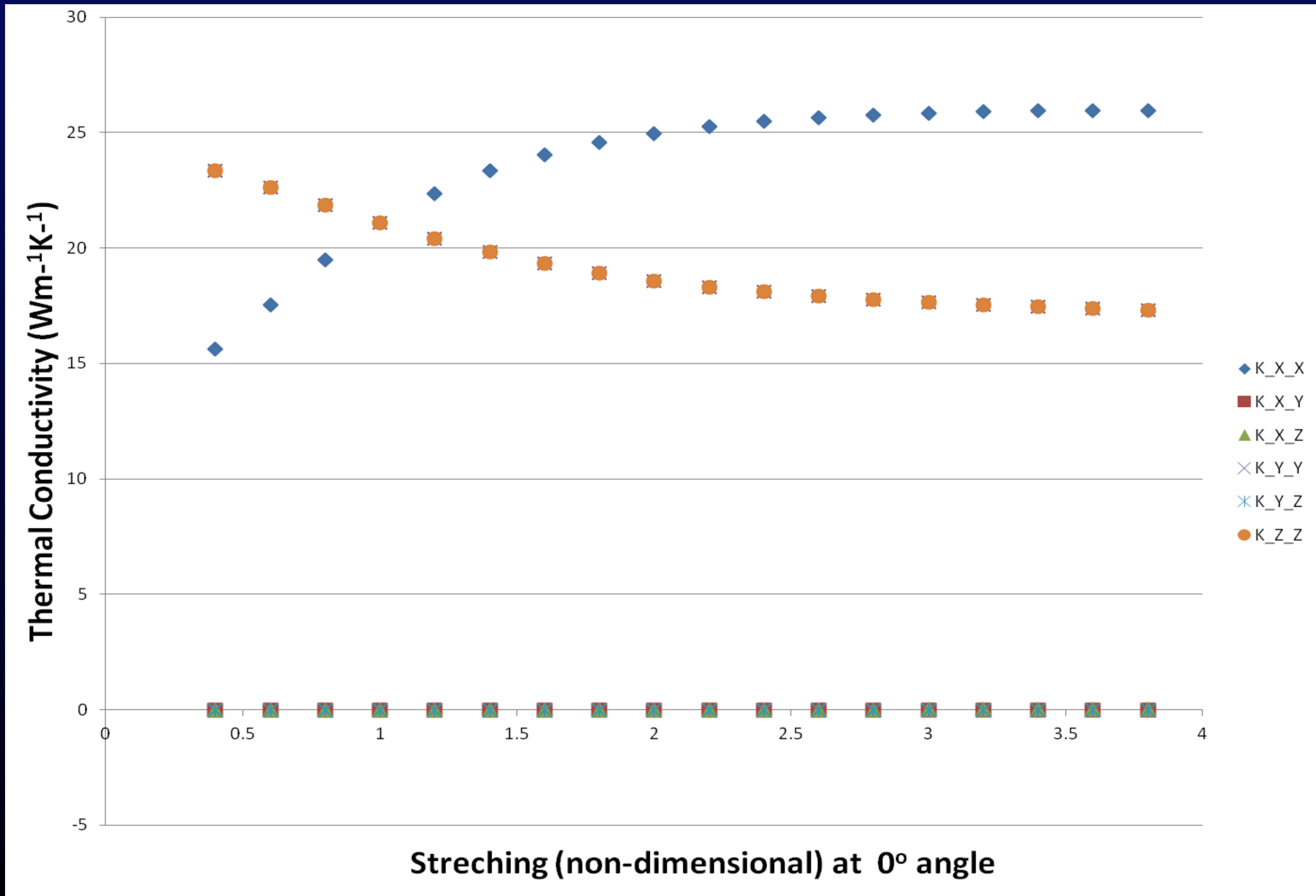


$\lambda_e \neq \lambda_{eff}^{s} + \lambda_{eff}^{f}$

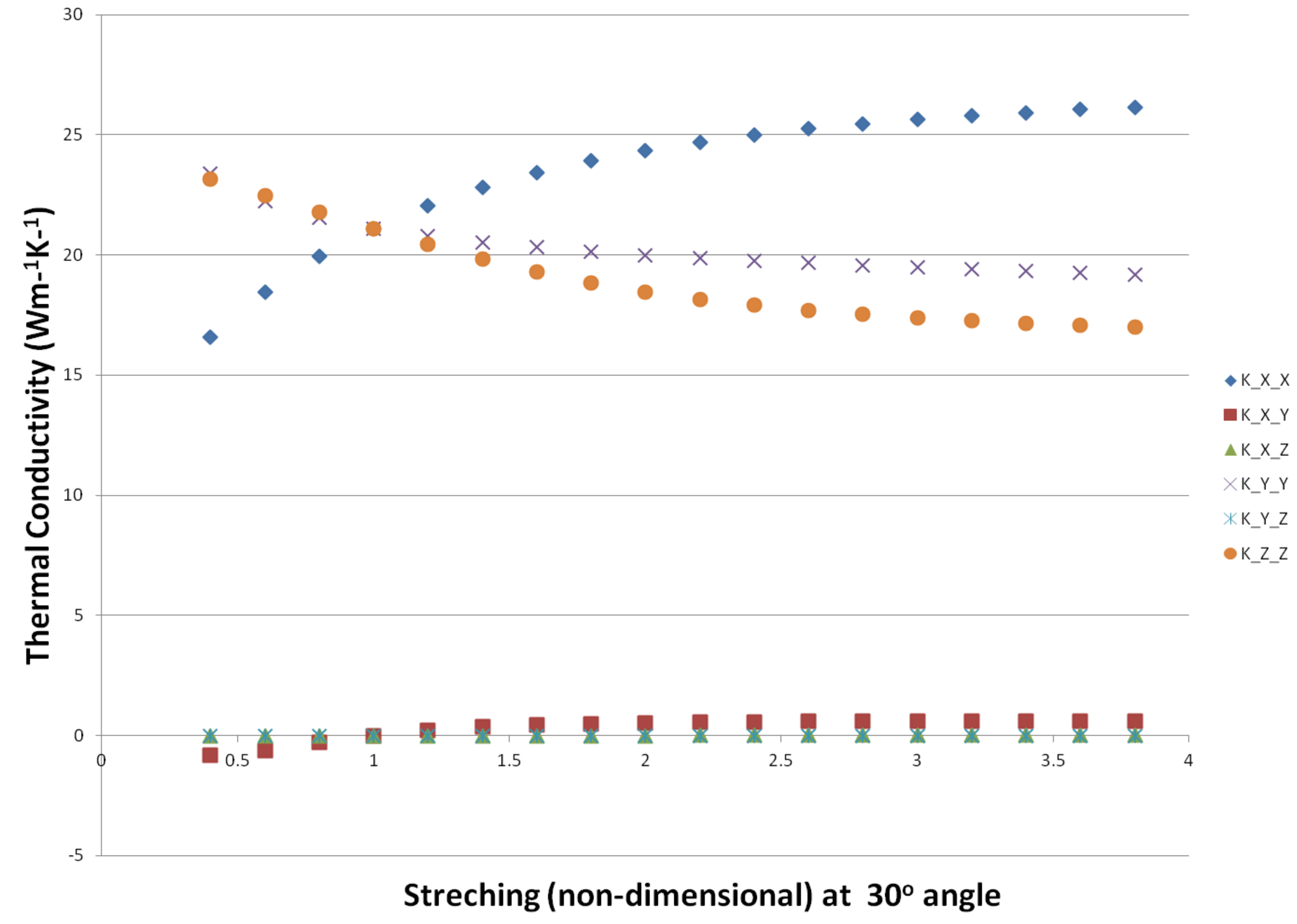
Composante Kxx



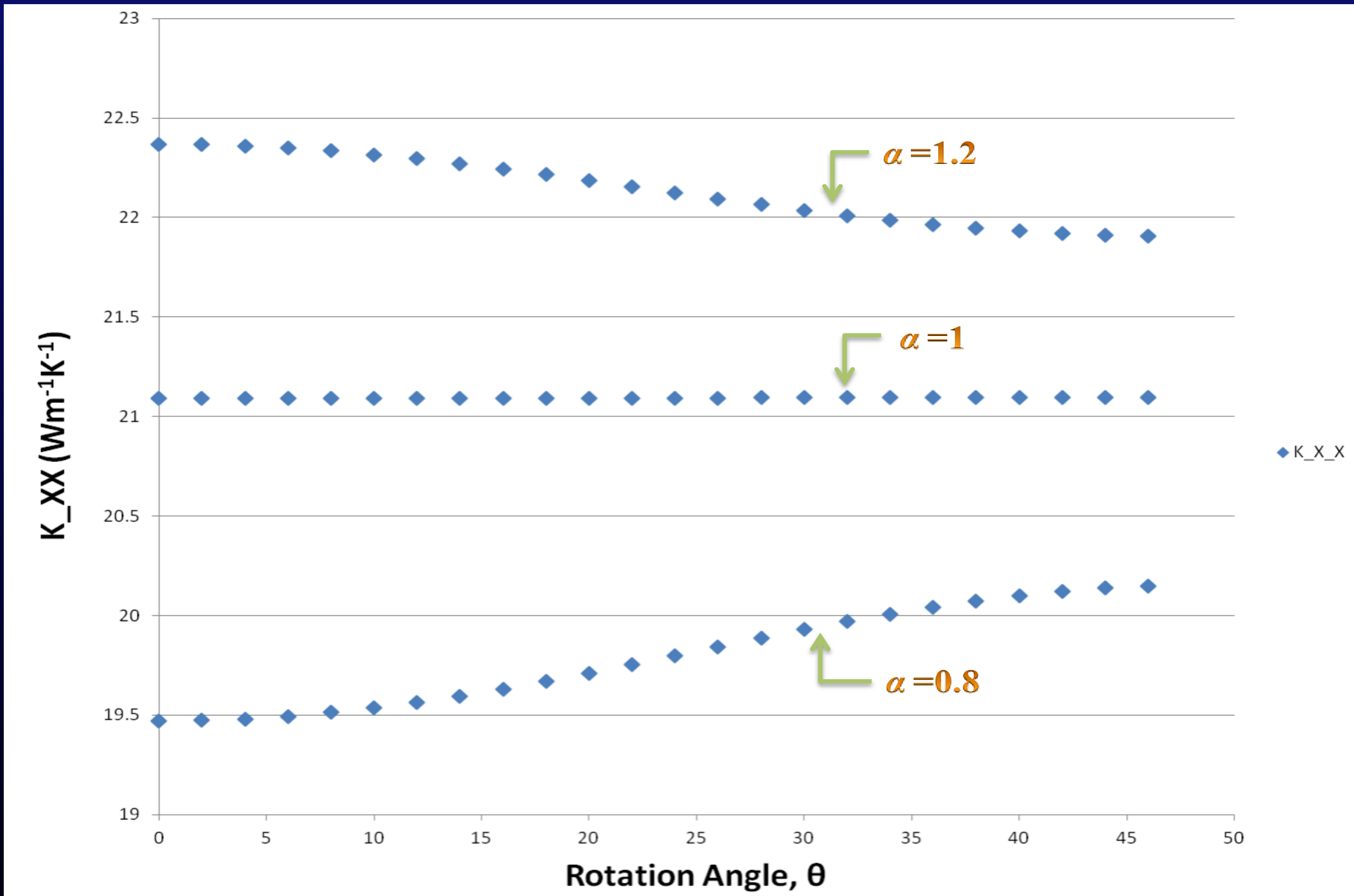
Results on Effective Thermal Conductivity



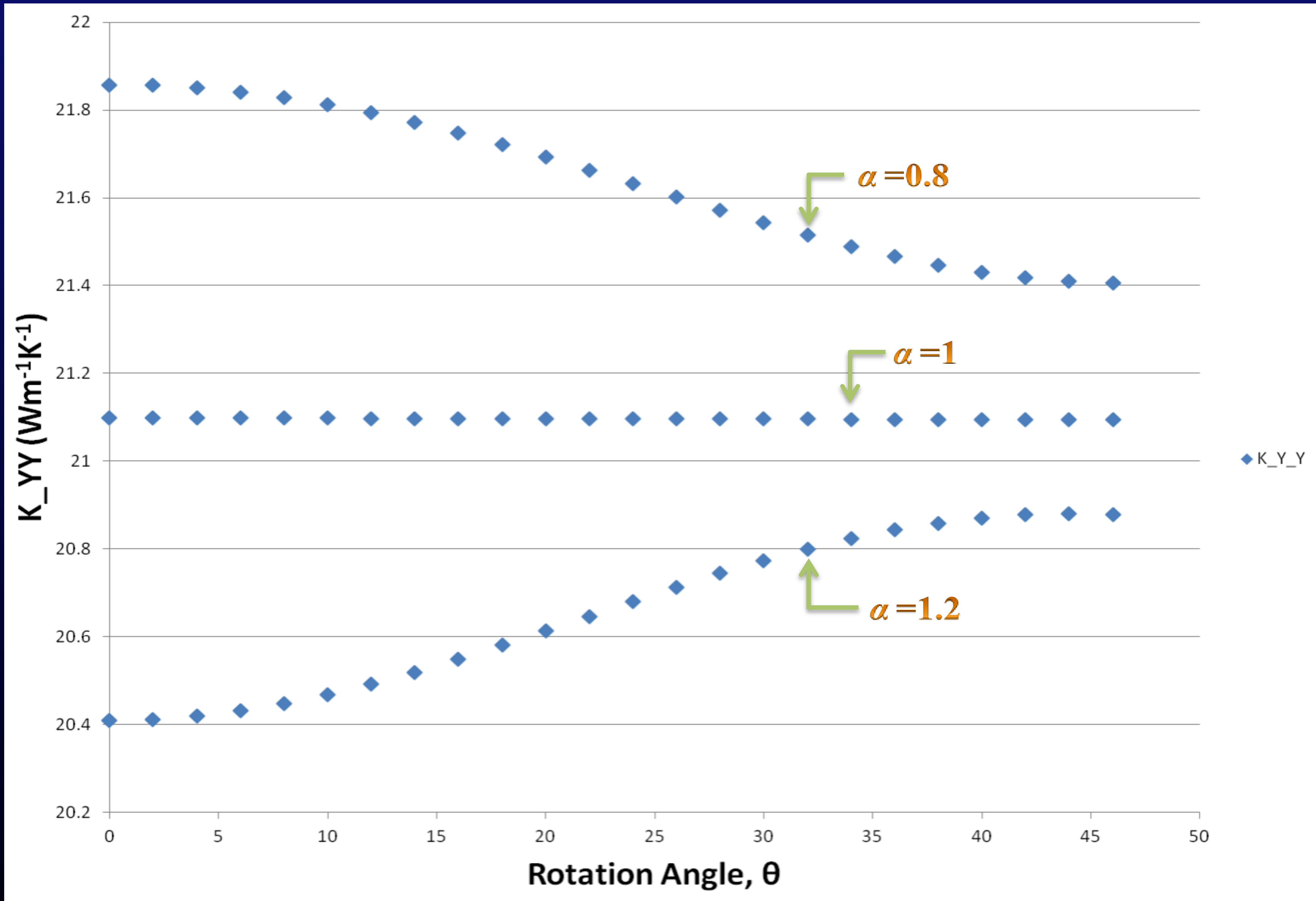
Thermal conductivity plot at 0^0 angle for various α for 80% porosity



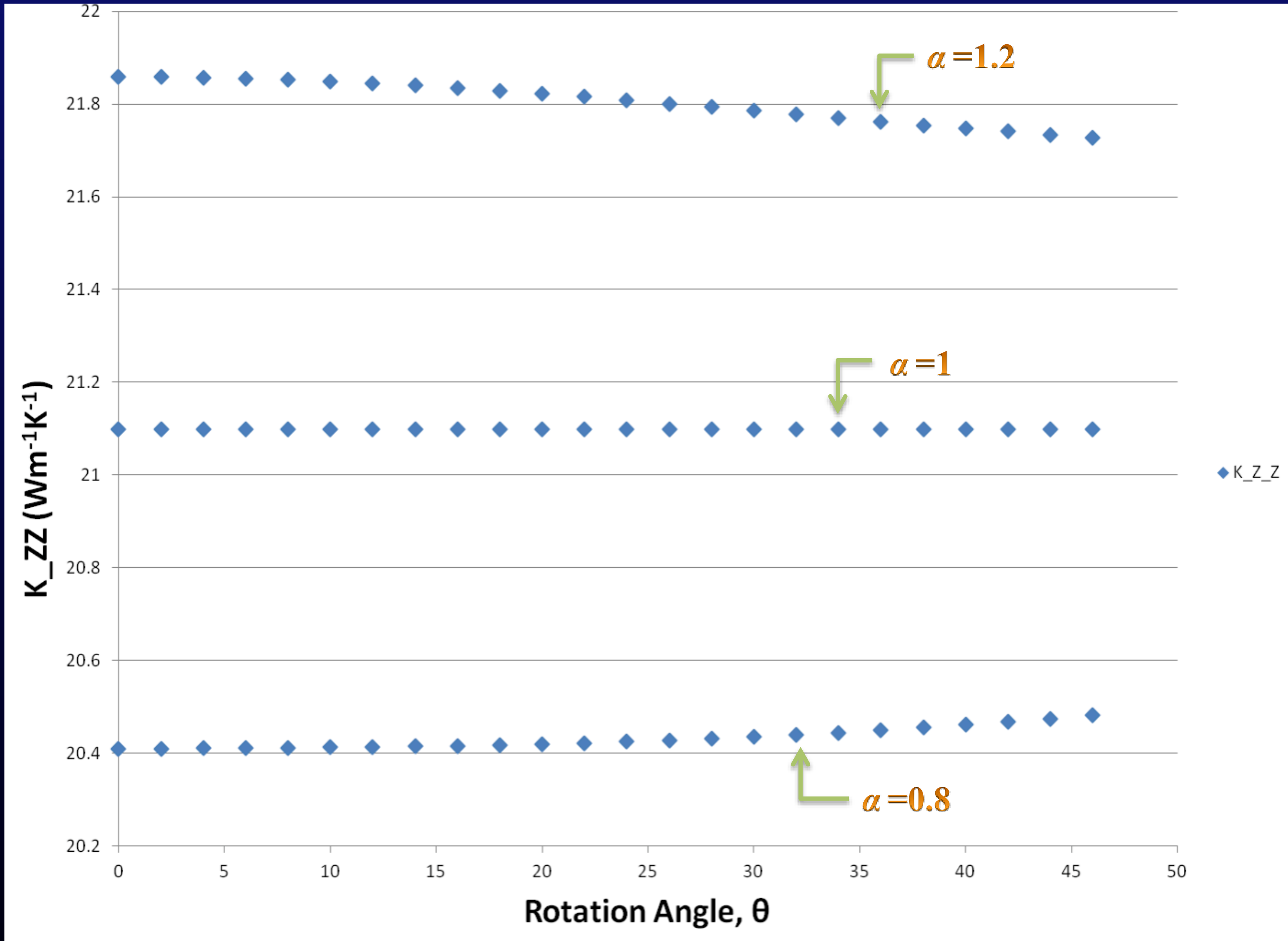
Thermal conductivity plot at 30^0 angle for various elongations for 80% porosity



Effect of elongation ratio, α on K_XX with rotation angle for 80% porosity



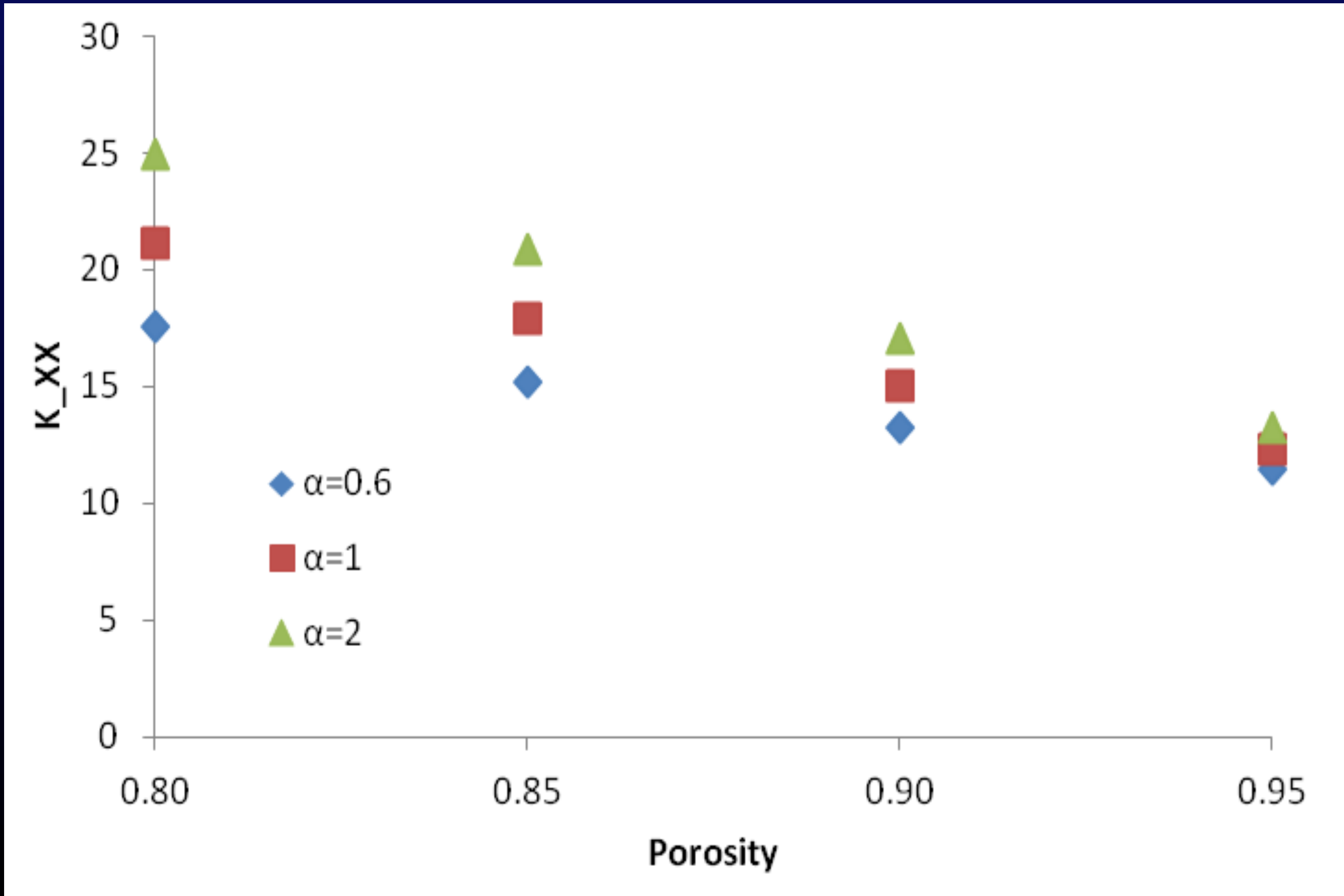
Effect of elongation ratio, α on K_YY with rotation angle for 80% porosity



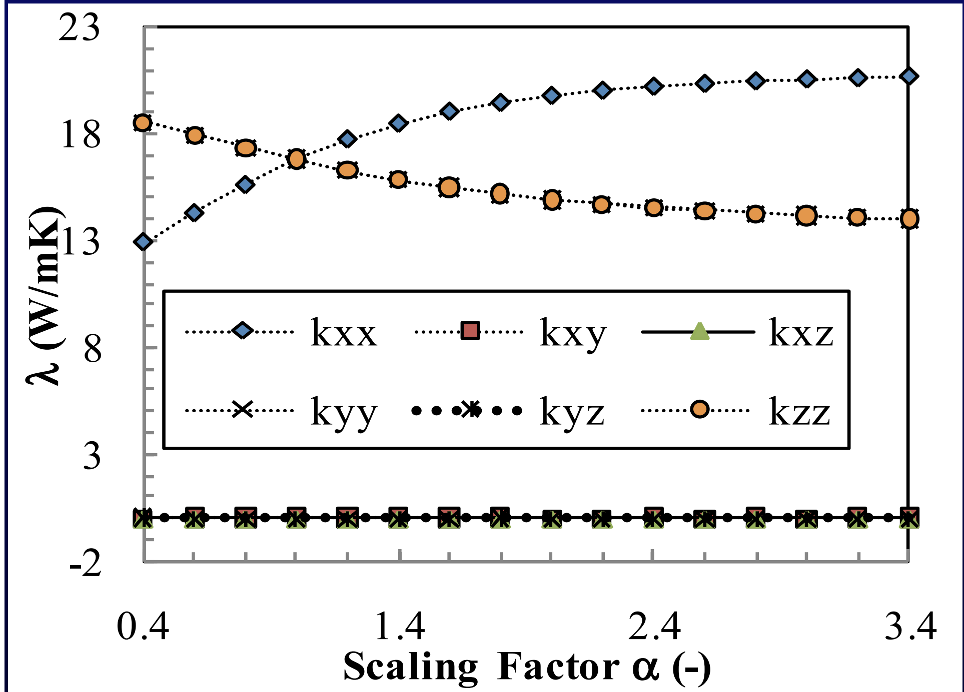
Effect of elongation ratio, α on K_ZZ with rotation angle for 80% porosity

Influence of porosity

- Comparisons are made at no-rotation



Pore Elongation

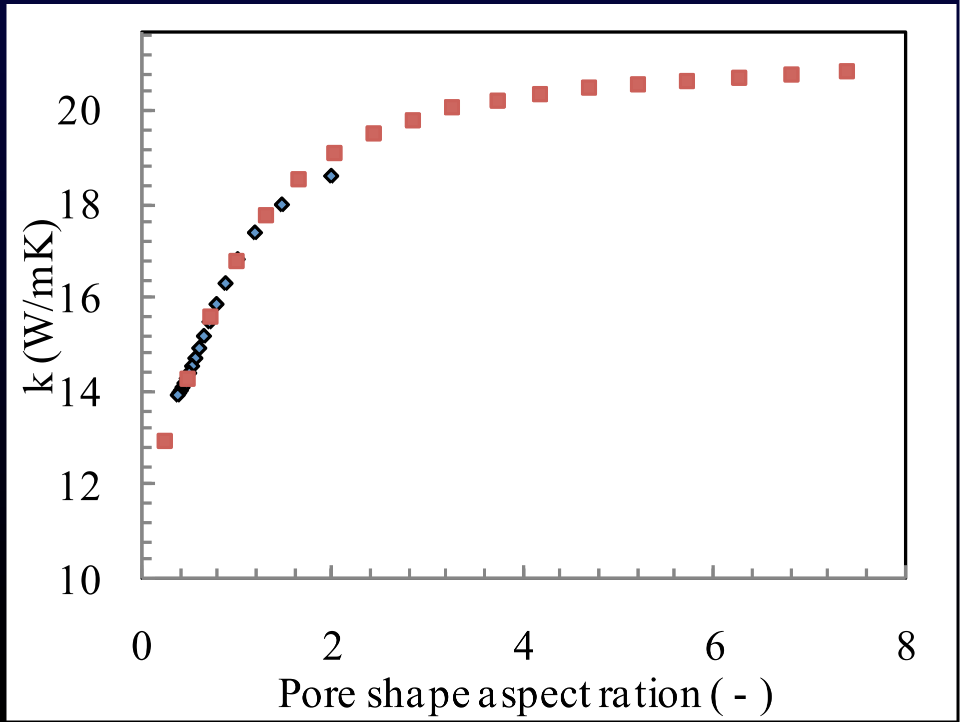


For q = 0°

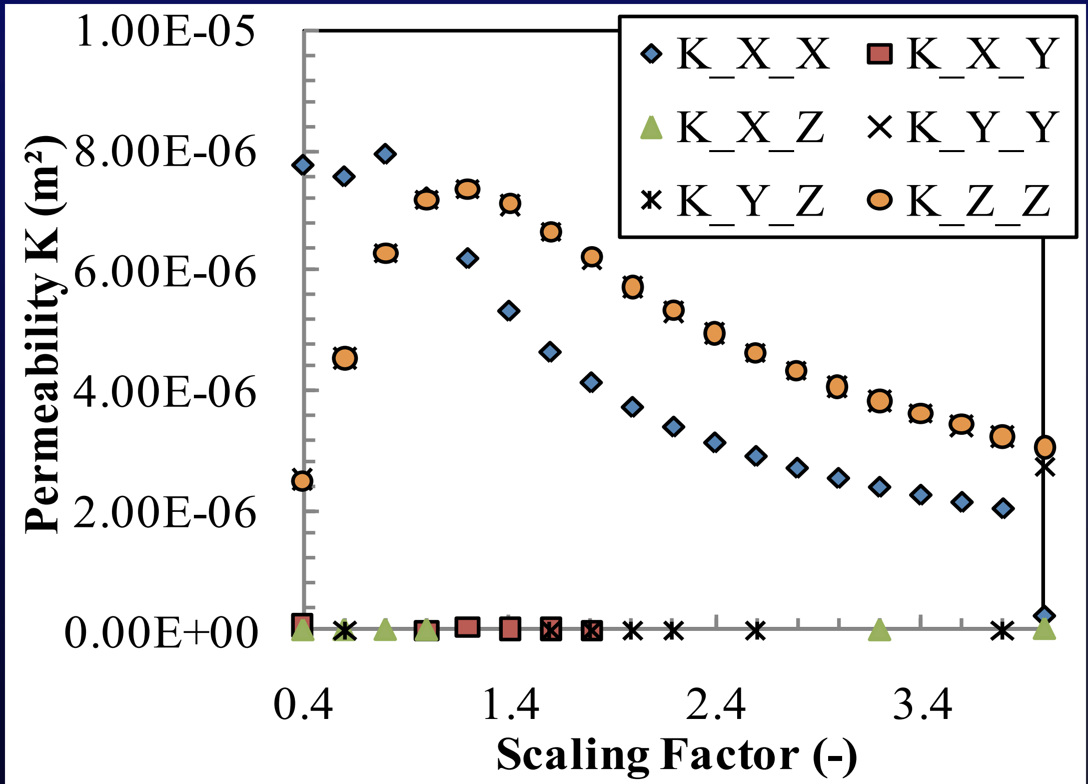
Increasing scaling factor X direction :
➔ increase conductivity in X

Effective conductivity followed pore shape aspect ratio and thus tortuosity

$$Aspect\ Ratio\_i = \frac{Scale\_i}{\sqrt{Scale\_j\ Scale\_k}}$$



Permeability



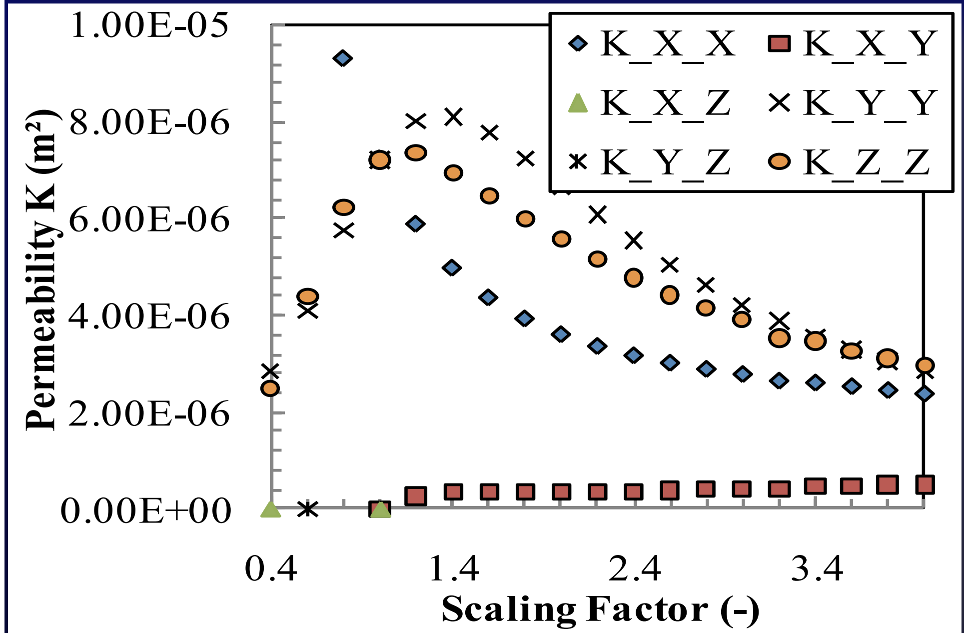
For q = 0°

Increasing scaling factor X direction :
➔ decrease permeability in X direction
➔increases conductivity in Y and Z direction

Permeability in X direction follows pore hydraulic diameter

$$D_{h_x} = \frac{2\ Scale\ Y\ Scale\ Z}{Scale\ Y +\ Scale\ Z}$$

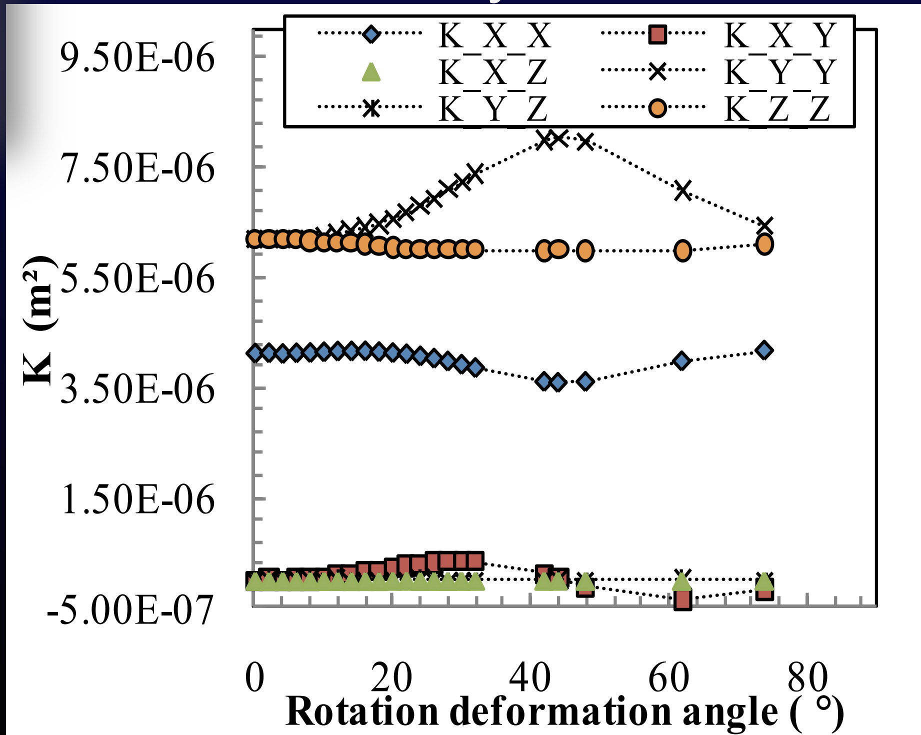
Permeability



For q = 40°

Behavior is completely changed

➔Permeability is on Y is

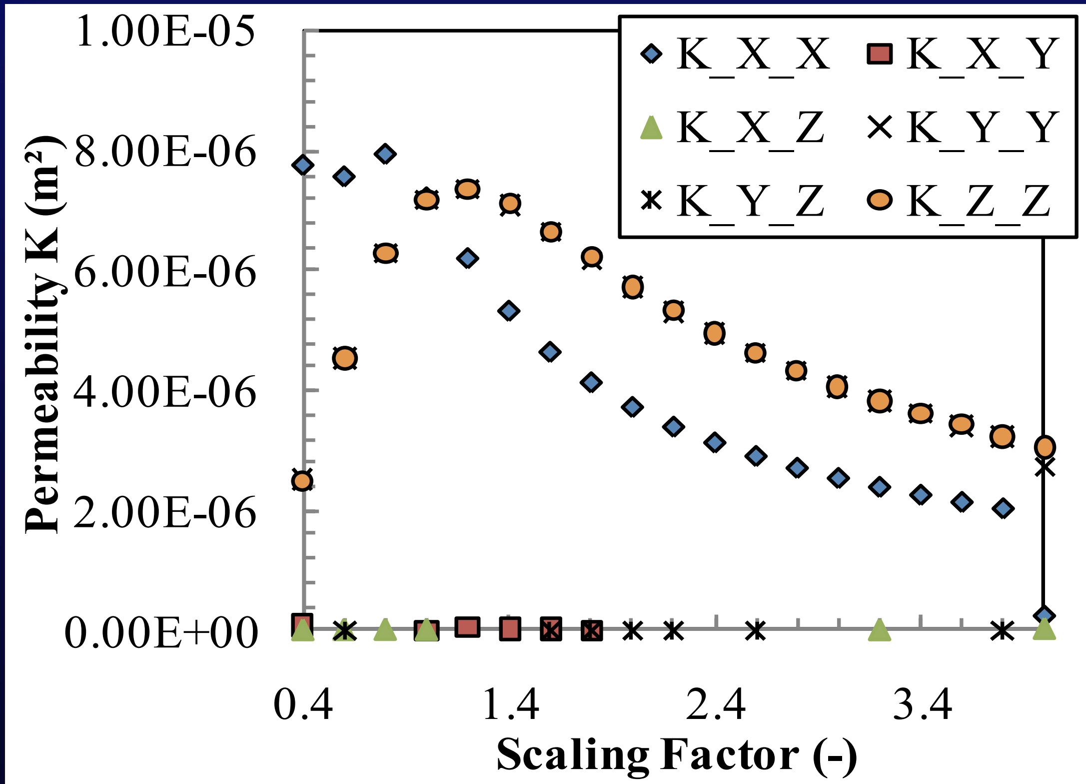


For a = 1.8

➔45° is geometric symmetry plane

➔ Non diagonal term appears

Permeability



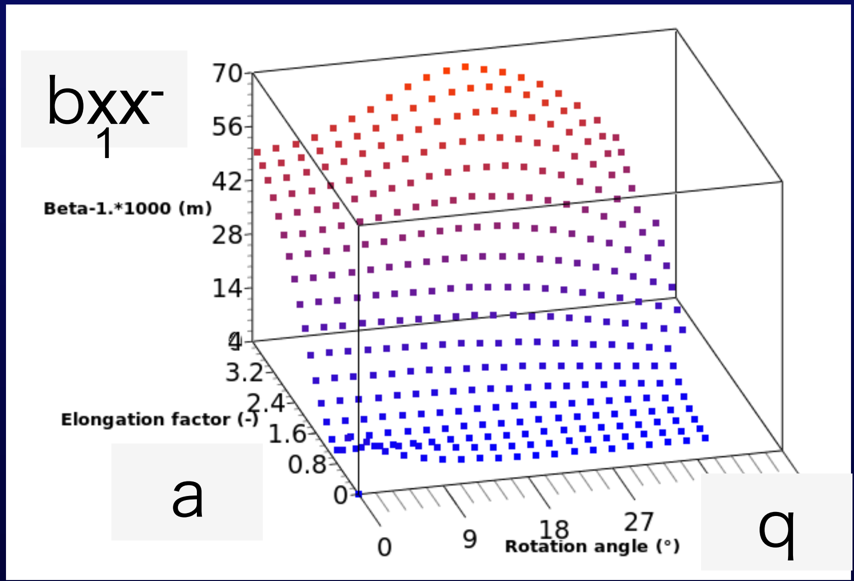
For q = 0°

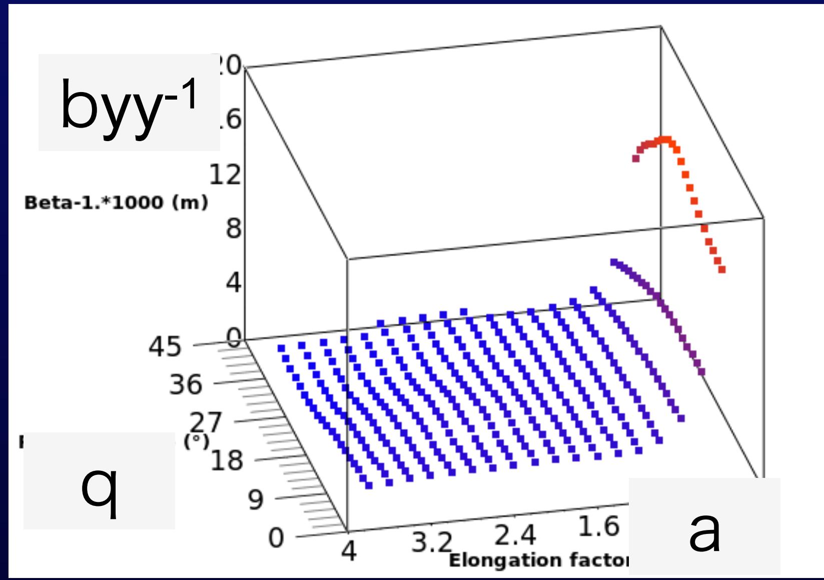
Increasing scaling factor X direction :
➔ decrease permeability in X direction
➔increases conductivity in Y and Z direction

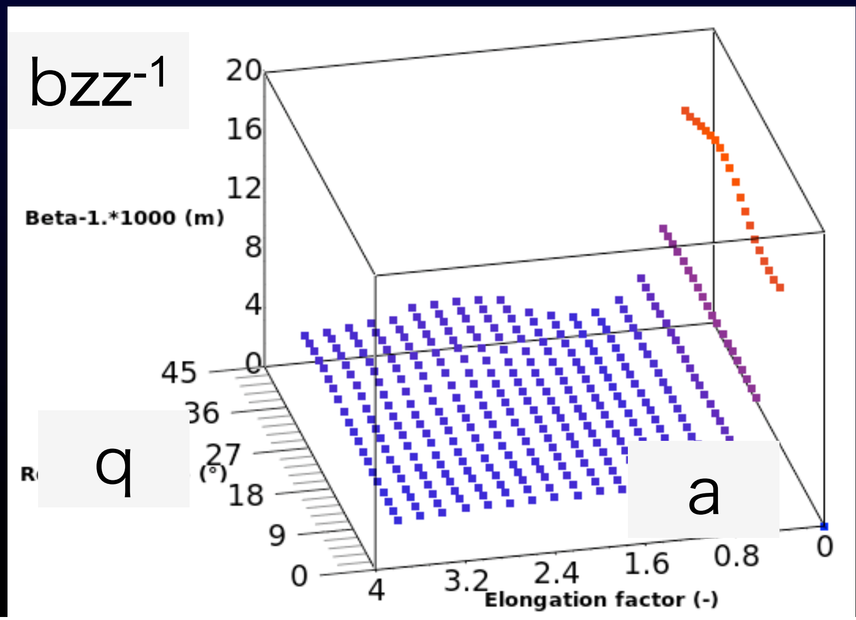
Permeability in X direction followed pore shape hydraulic diameter

$$D_{h_x} = \frac{2\ Scale\ Y\ Scale\ Z}{Scale\ Y\ Scale\ Z}$$

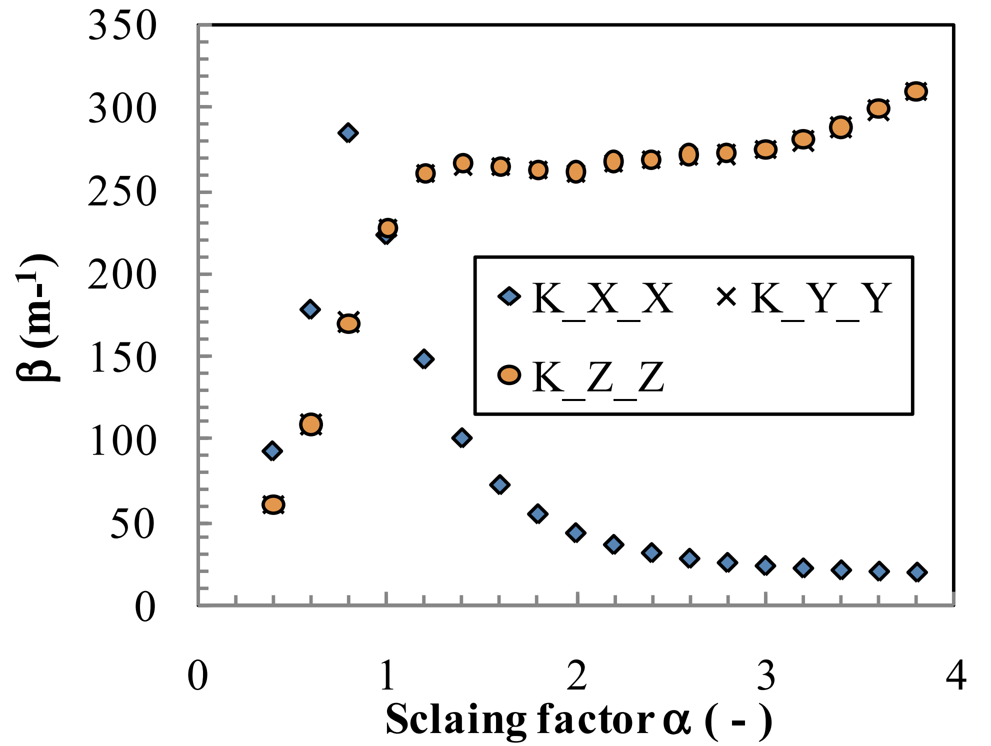
Inertia Coefficient





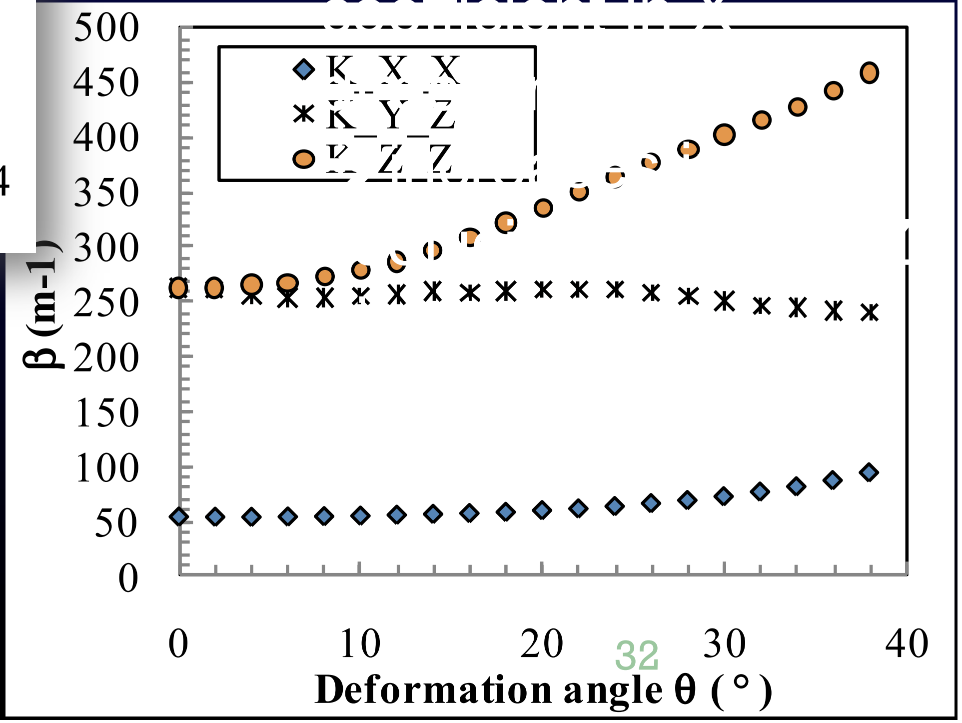


Inertia Coefficient



For q = 0°

Increasing scaling factor X direction :
→ decrease inertia coefficient in X

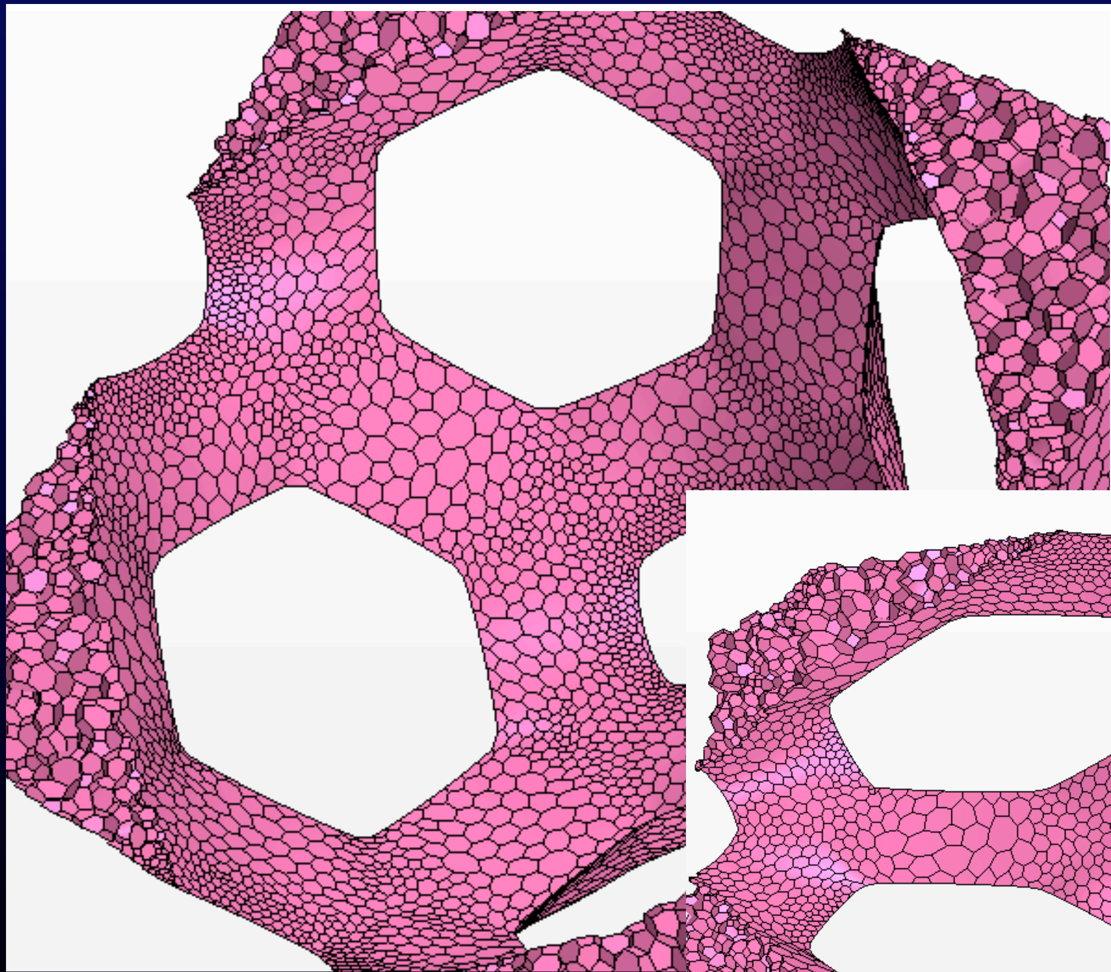


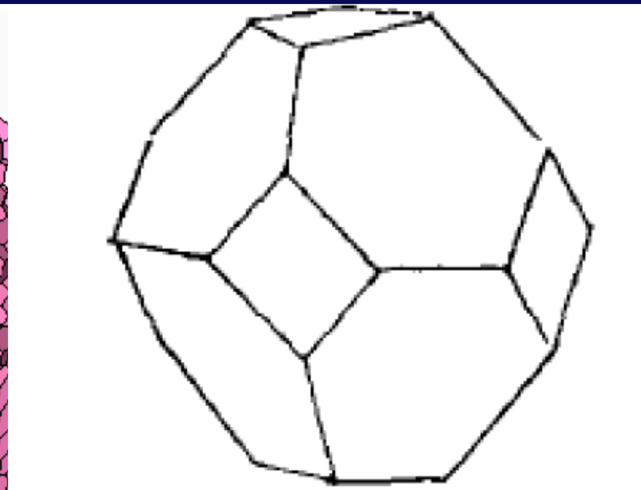
Conclusion

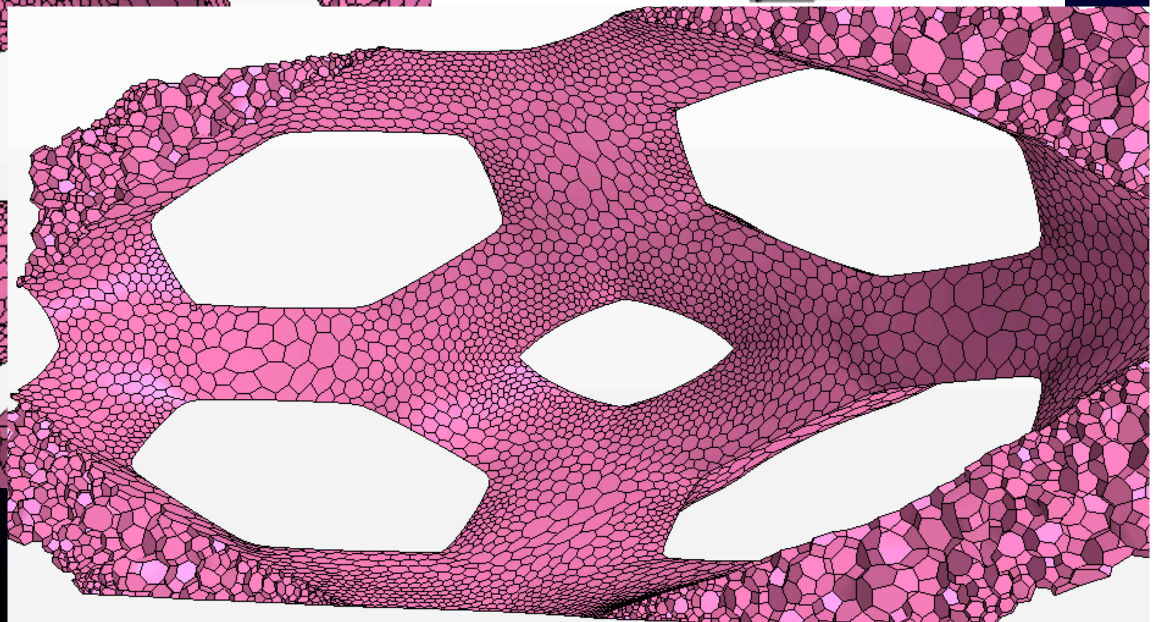
- Propriétés de transports dépendent de la forme
- pour chaque type d'objet il existe des correlations
- compréhension des relations encore insuffisante
- dispersion des résultats
- multiplicité des paramètres

Thank You For Your Attention !

La cellule unitaire







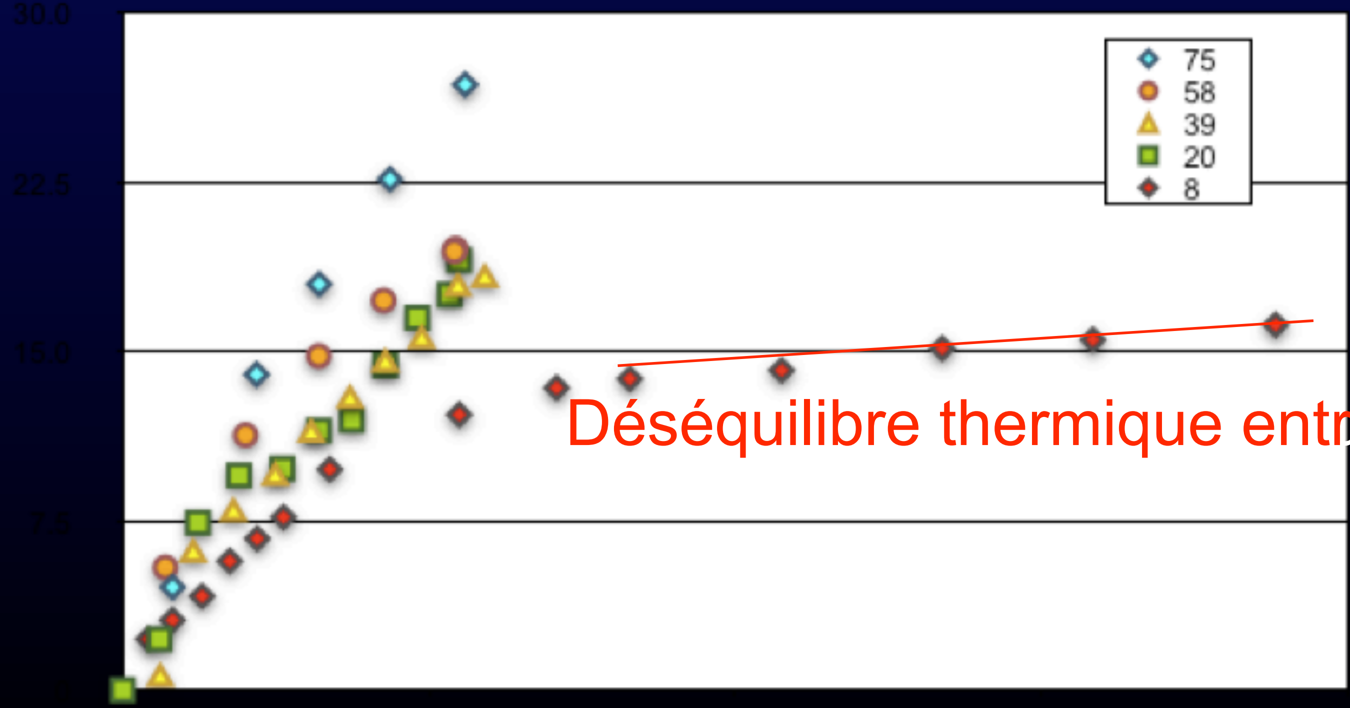
Courbe d'ébullition

Apparition de l' ébullition pour des surchauffes très faibles

Flux critique très important

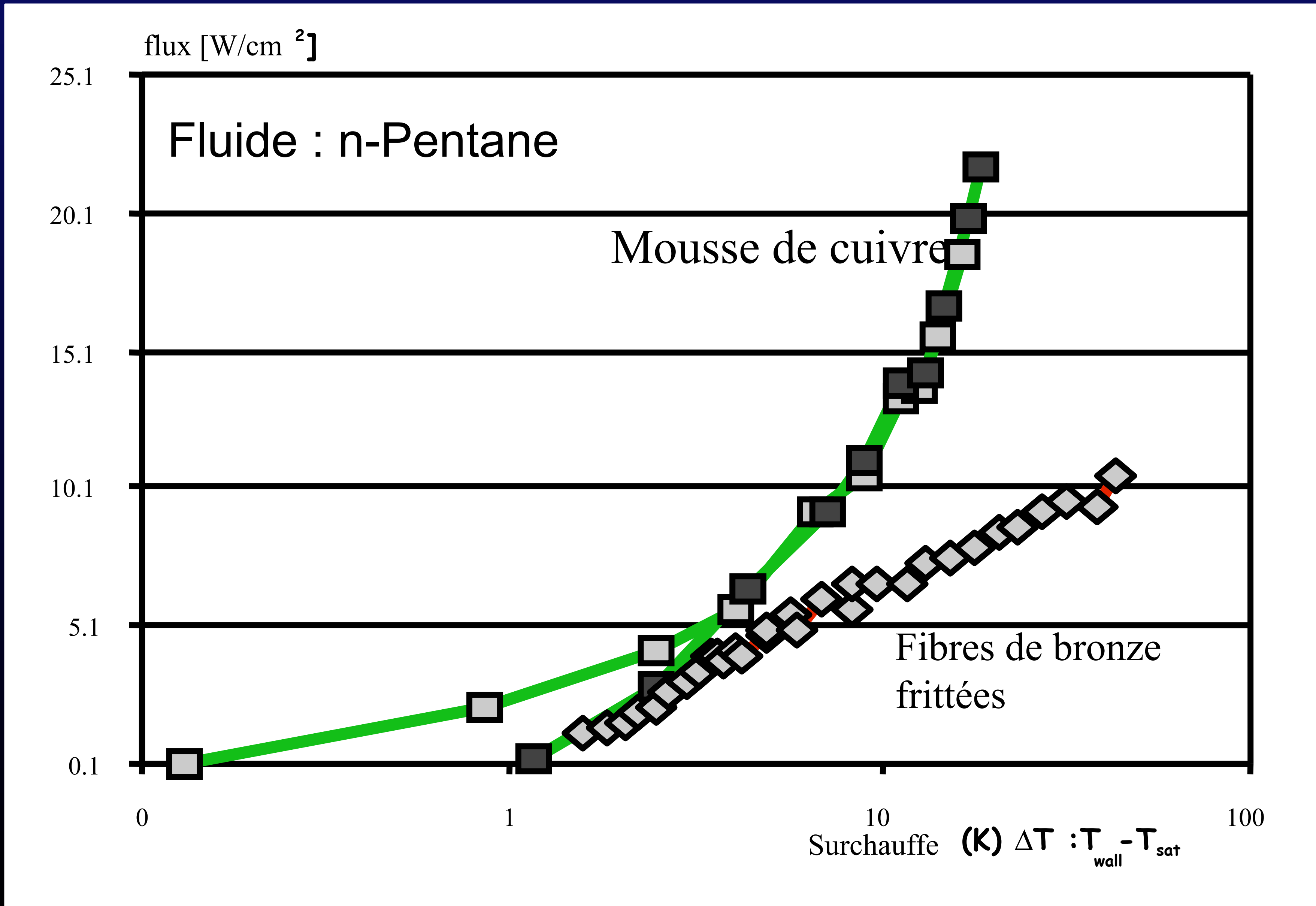
$G > 10\ kgm^{-2}s^{-1}$, $Qc > 30\ W\ cm^{-2}$

Déséquilibre thermique observable uniquement pour les plu

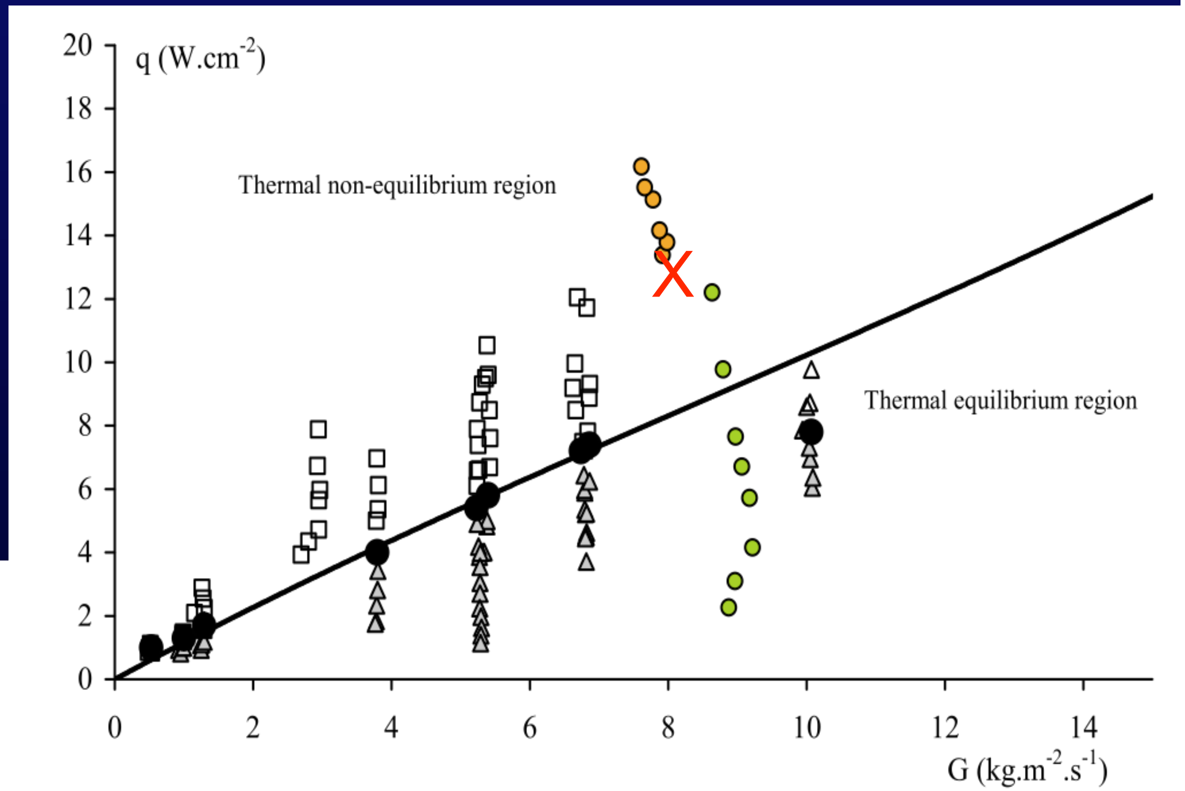


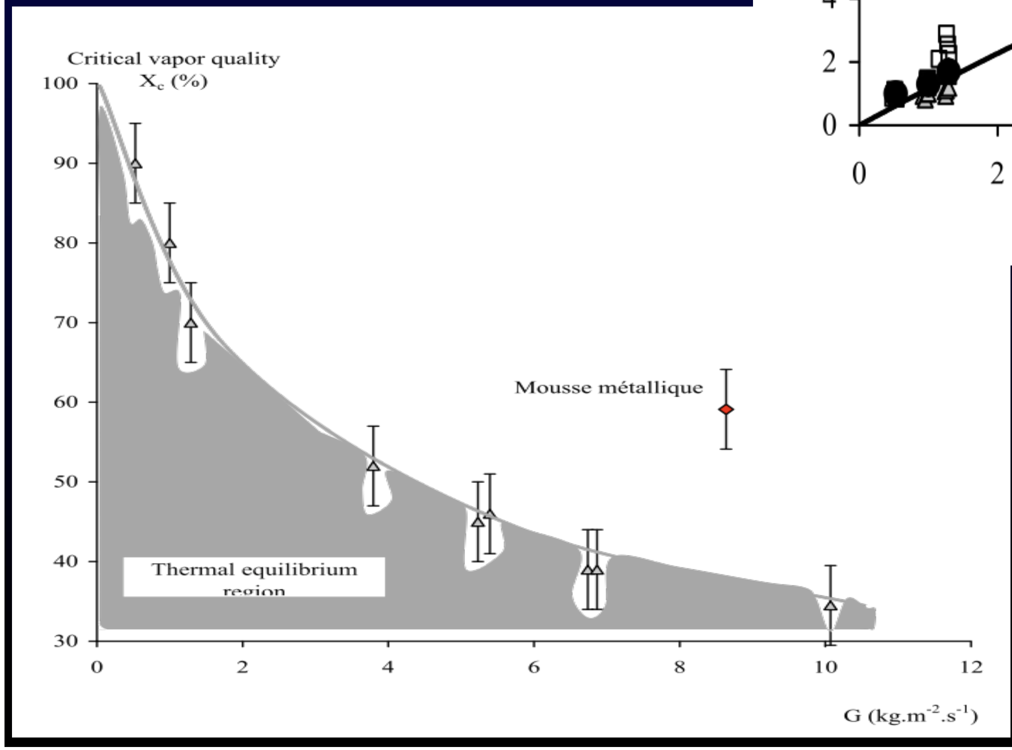
Déséquilibre thermique entre fluides

Courbe d'ébullition Comparaison mousse - fibres

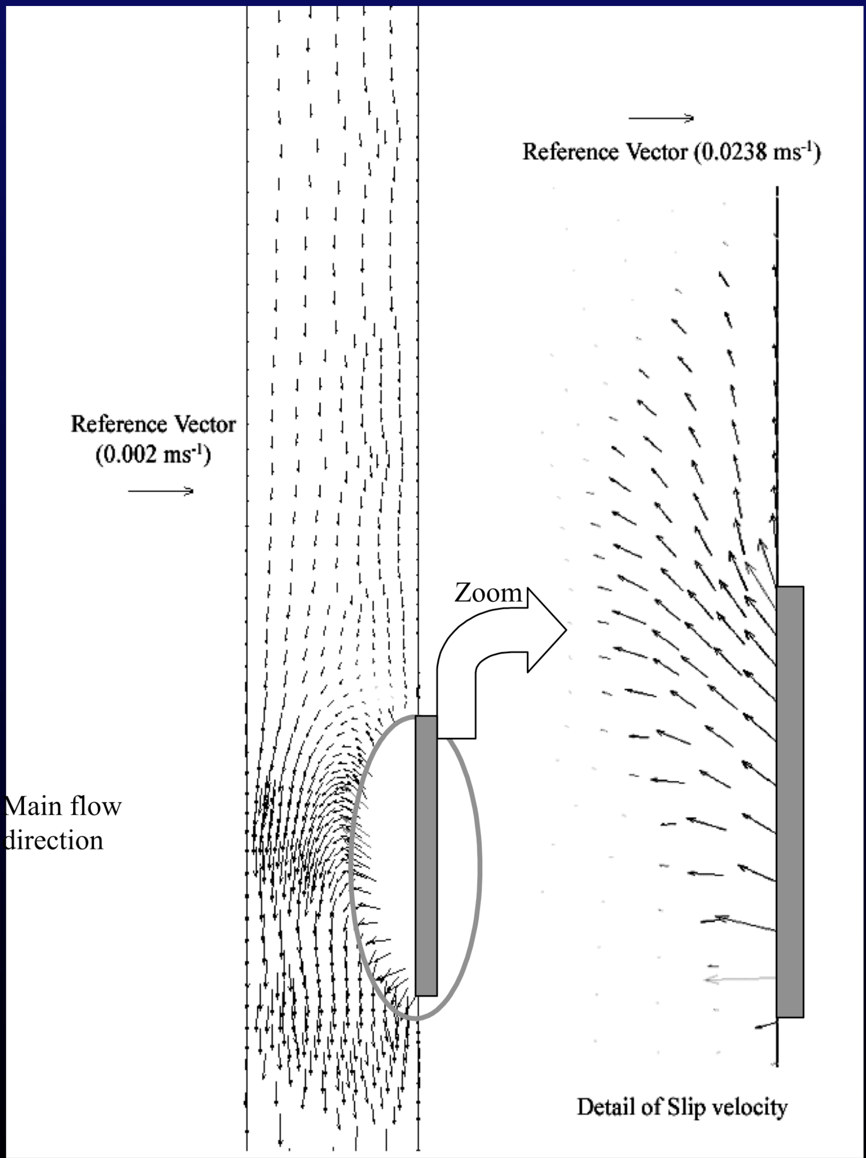


Courbe critique





Intensification des transferts

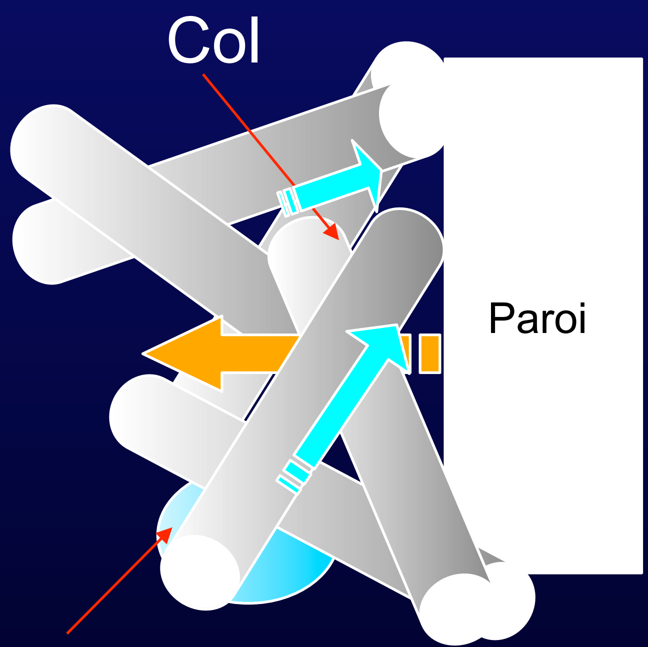


Vitesse de glissement

Mécanismes

- Changement de phase au voisinage de la paroi
- Réalimentation en liquide
- Evacuation de la vapeur
- Effet ailette de la matrice solide
  - Apport thermique au cœur de l'écoulement
  - Accroissement des surfaces d'évaporation

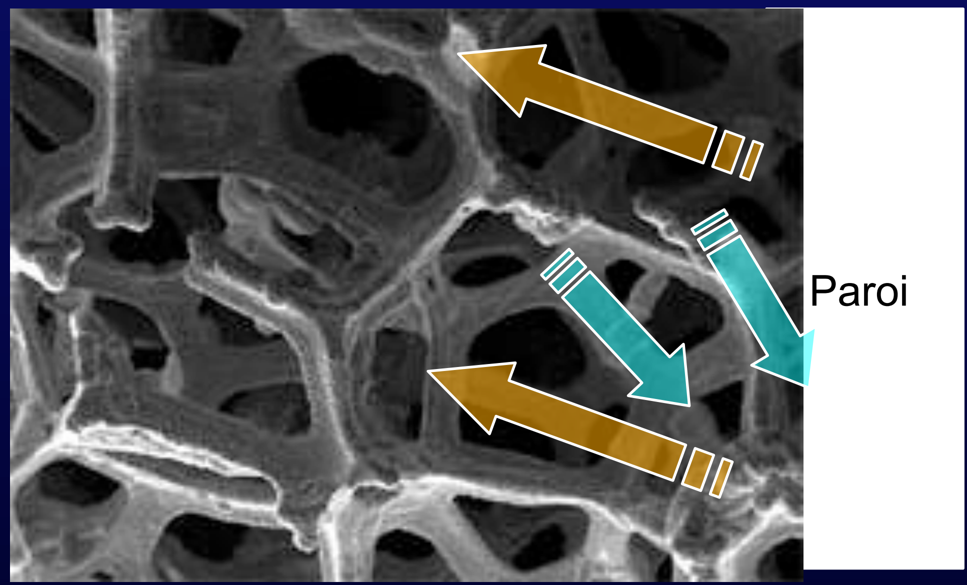
Interprétation « hydrodynamique »



Goutte au voisinage du contact/col

Cols limitent écoulements (blocage par bulle ou goutte

Forme convexe ? films liquide



Pas de constriction : ecoulements liquide vapeur à contre courant

Forme concave favorise l’ alimentation par des films liquide