Porosity dependence of thermal conductivity in UO_2 nuclear fuels

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Porosity dependence of thermal conductivity in UO_2 nuclear fuels

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55th Annual Technical Meeting SES

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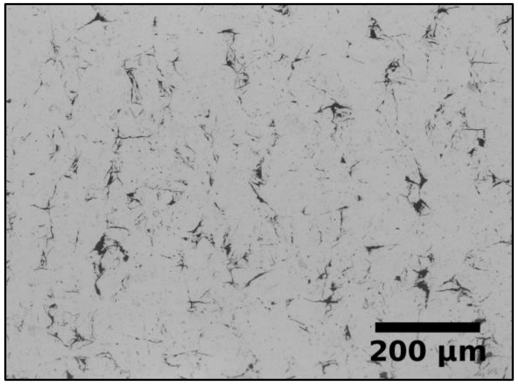
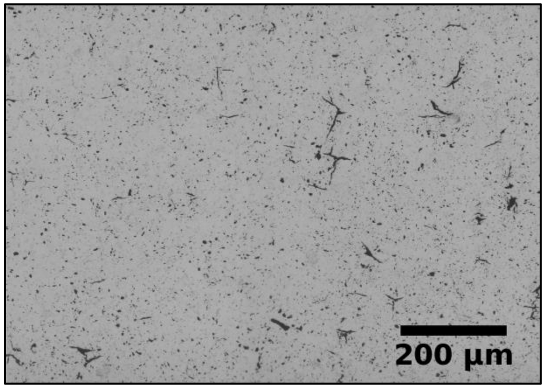
Limits of classic conductivity UO_2 laws

→ One parameter only: % total porosity

- Example of two UO_2 fuels with the same % porosity



UO_2 fuel A



UO_2 fuel B

% total porosity (%)	4,1 ± 0,1	
Thermal diffusivité α ($mm^2.s^{-1}$)	2,85 ± 0,04	2,99 ± 0,001

$$\left(\frac{\lambda_A}{\lambda_B}\right)_{exp} = \left(\frac{\alpha_A}{\alpha_B}\right)_{exp} = 0{,}93 \neq \left(\frac{\lambda_A}{\lambda_B}\right)_{classic\lambda\_UO_2\_laws} = 1$$

- Description of UO_2 fuels with only the % total porosity is not adequate to describe the thermal behaviour of these fuels.

SCIENTIFIC APPROACH

Objective

- Determination of a new thermal behaviour law which gives the influence of porosity (shape, orientation and network) on thermal conductivity for non-irradiated UO_2 fuels

Presentation outline

Microstructure modelling

↓

Thermal behaviour law modelling
- Using an homogenization approach

↓

Determination of microstructural descriptors
- To feed the thermal behaviour model

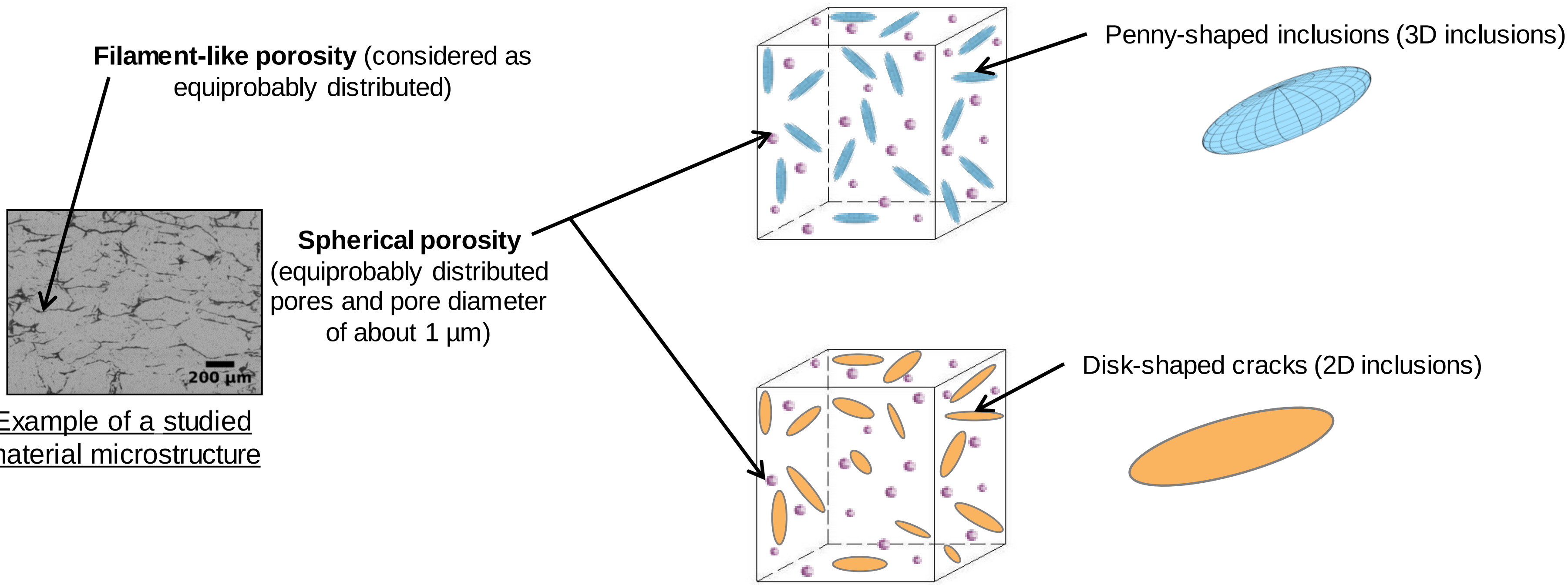
↓

Evaluation of the developed models
- Comparison to experimental measurements obtained by Flash method

MICROSTRUCTURE MODELLING

Descriptions of the studied material

- Two porosity types classified by pore morphology embedded into an urania matrix
- <u>Two</u> different descriptions of the studied material have been considered.



<u>Example of a studied material microstructure</u>

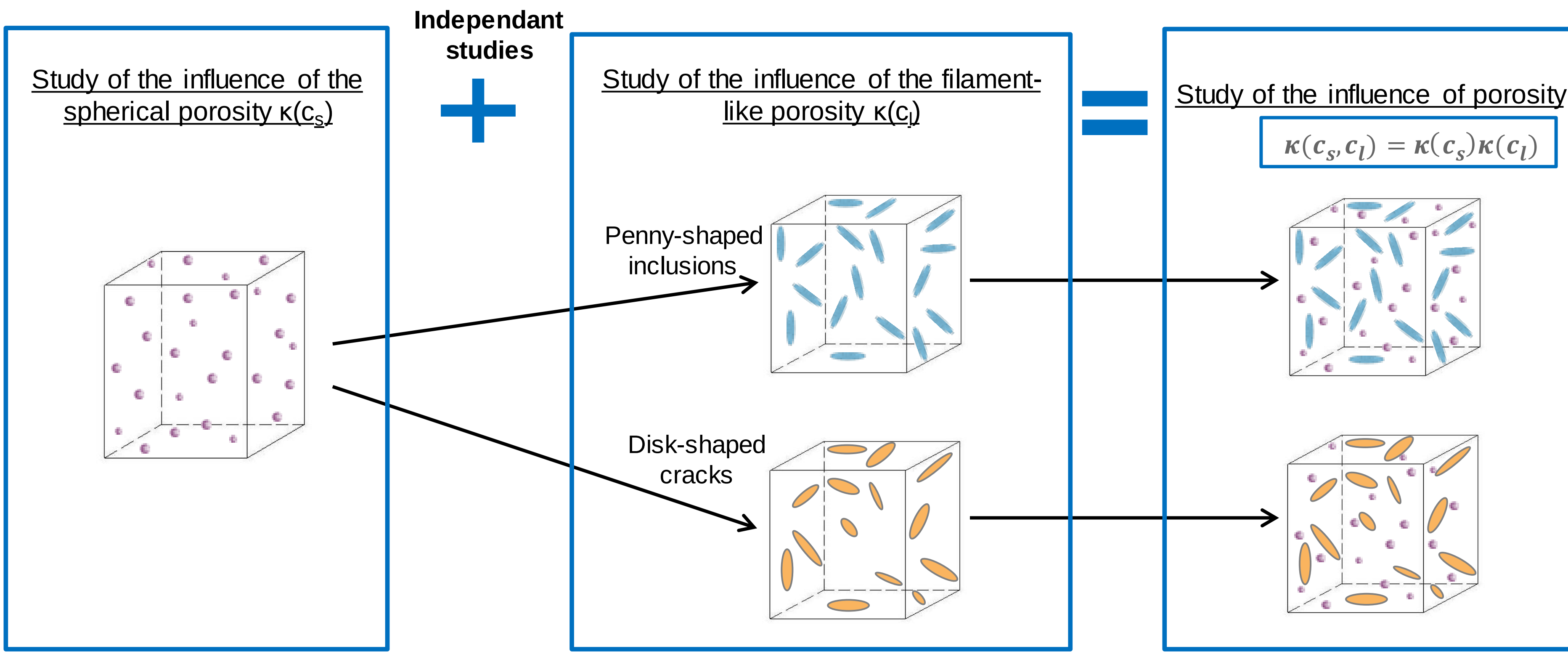
THERMAL BEHAVIOUR LAW MODELLING

Homogenization approach

- Study of the characteristic dimensions of both porosity types

➔ Spatial scale separation between both porosity families

- Opportunity to study separately the influence of each family



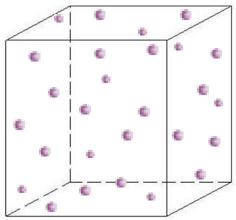
THERMAL BEHAVIOUR LAW MODELLING

Models developed

$$\kappa(c_s, c_l) = \kappa(c_s)\kappa(c_l)$$

➔ **Determination of microstructural descriptors**

Study of the influence of the spherical porosity $\kappa(c_s)$



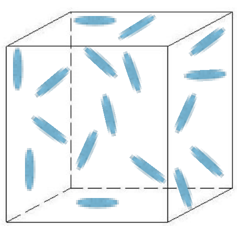
« Diluted medium » model for spherical pores equiprobably distributed in the matrix (first-order approximation of Maxwell model*)

$$\kappa(c_s) = \left(1 - \frac{3}{2} c_s\right) I$$

→ **% spherical porosity**

Study of the influence of the lenticular porosity $\kappa(c_l)$

Penny-shaped inclusions



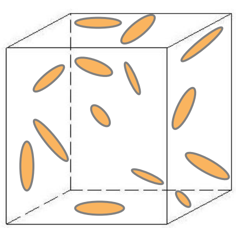
« Diluted medium » model** for penny-shaped pores equiprobably distributed in the matrix (first-order approximation in c_l/ω)

$$\kappa(c_l) = \left(1 - \frac{2}{3\pi}\frac{c_l}{\omega}\right) I$$

→ **% filament-like porosity**

→ **Penny-shaped inclusion aspect ratio**

Disk-shaped cracks



« Diluted medium » model*** for disk-shaped cracks equiprobably distributed in the matrix

$$\kappa(\rho_f) = \left(1 - \frac{8}{3}\rho_f\right) I$$

→ **Crack density**

* *J.C. MAXWELL, A treatise on electricity and magnetism, 1873*

** *H. L. DUAN et al., Phys. Rev. B* ***73****(17): 174203(13), May 2006*

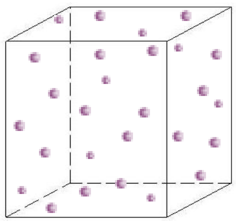
*** *B. SHAFIRO et M. KACHANOV, J. Appl. Phys., Vol. 87, No. 12, 2000*

Determination of microstructural descriptors

$$\boldsymbol{\kappa}(\boldsymbol{c_s},\boldsymbol{c_l}) = \boldsymbol{\kappa}(\boldsymbol{c_s})\boldsymbol{\kappa}(\boldsymbol{c_l})$$

➔ Evaluation of the models representativeness

Study of the influence of the spherical porosity κ(c_S)

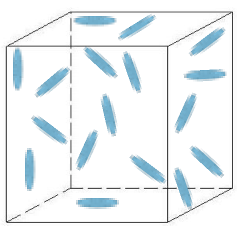


$$\boldsymbol{\kappa}(\boldsymbol{c_s}) = \left(1 - \frac{3}{2}c_s\right)\boldsymbol{I}$$

% spherical porosity → Bromobenzene saturation method

Study of the influence of the lenticular porosity κ(c_l)

Penny-shaped inclusions

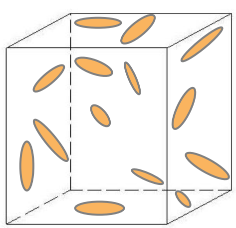


$$\boldsymbol{\kappa}(\boldsymbol{c_l}) = \left(1 - \frac{2}{3\pi}\frac{c_l}{\omega}\right)\boldsymbol{I}$$

% filament-like porosity → Bromobenzene saturation method

Penny-shaped inclusion aspect ratio → Image analysis

Disk-shaped cracks



$$\boldsymbol{\kappa}(\boldsymbol{\rho_f}) = \left(1 - \frac{8}{3}\rho_f\right)\boldsymbol{I}$$

Crack density → Image analysis

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** *H. L. DUAN et al., Phys. Rev. B* ***73****(17): 174203(13), May 2006*

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MODEL VALIDATION

Principle

- Comparison of the developed models to thermal diffusivity measurements (<u>indirect</u> thermal conductivity measurements)

$$\lambda = \rho c \alpha$$

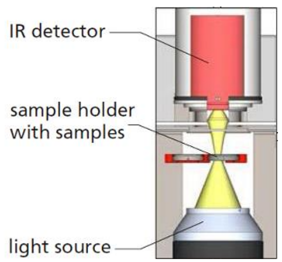
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) ← λ

Density ($kg \cdot m^{-3}$) ← ρ

Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$) ← c

Thermal diffusivity ($m^2 \cdot s^{-1}$) ← α

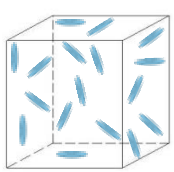
- Protocol of thermal diffusivity measurements by Flash method*



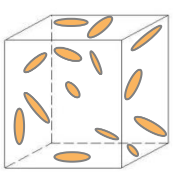
<u>Basic diagram of the Flash method apparatus</u>

  - Delivery of a short-term excitation pulse to the sample
  - Heat transfer by conduction
  - Thermogram recorded at the rear of the sample
  - Signal fitting to the Cape-Lehman model (which considers radial and facial thermal losses and pulse duration)

Evaluation of the representativeness of the filament-like model



Penny-shaped inclusion model

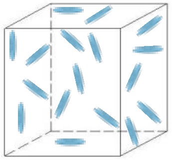


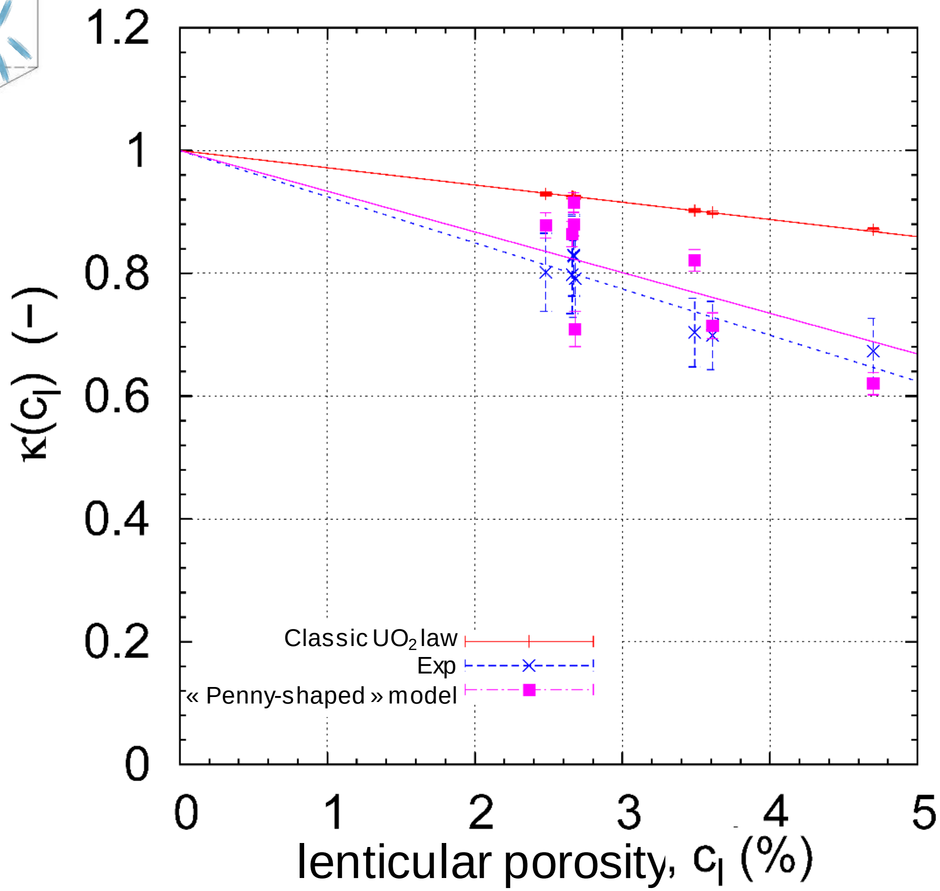
Disk-shaped crack model
➔ **<u>Still in process</u>**

** Netzsch – LFA 467 Hyper Flash, https://www.netzsch-thermal-analysis.com/us/products-solutions/thermal-diffusivity-conductivity/lfa-427/ Last accessed on: 2018-09-24.*

MODEL VALIDATION

Evaluation of the penny-shaped inclusion model





Evaluation of the representativeness of the "penny-shaped" model

+ Penny-shaped inclusion model more representative than the classic conductivity UO_2 law

- Remaining model/experience bias which does not allow a distinction between UO_2 fuels based on their thermal behaviour

$$\kappa_{model}(c_l) = \left(1 - \frac{2}{3\pi}\frac{c_l}{\omega}\right) I$$

Bias induces by the characterization of the aspect ratio ω

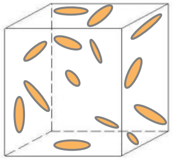
CONCLUSIONS AND OUTLOOK

Conclusions

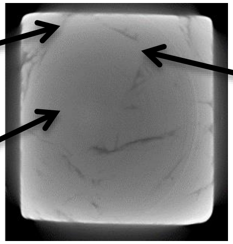
- Development of the penny-shaped inclusion model which is more representative than classic UO_2 laws ➔ The modelling of porosity dependency of thermal conductivity in UO_2 nuclear fuels is improved.
- The penny-shaped inclusion model is not sufficient to discriminate different UO_2 nuclear fuels. ➔ Necessity to improve modelling

Work in progress

- Finalization of the disk-shaped crack model
  - Determination of the crack density ρ_f
  - Evaluation of the representativeness of filament-like pores by disks
- Evaluation of filament-like pore interconnectivity with additional porosity imaging



$$\boldsymbol{\kappa}(\boldsymbol{\rho_f}) = \left(1 - \frac{8}{3}\rho_f\right)\boldsymbol{I}$$



3D tomography experiment (slice of a UO2 sample)

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