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Hydrodynamic Experimental and Numerical Study of Micro-fabricated Regenerator.

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Plan

Introduction:
- Context.
- Previous works.
- Objectives.

Numerical study:
- Mesh, mathematical model and solver.
- Direct numerical simulation.
- Results and discussion.

Experimental study:
- Micro-machining of regenerators samples.
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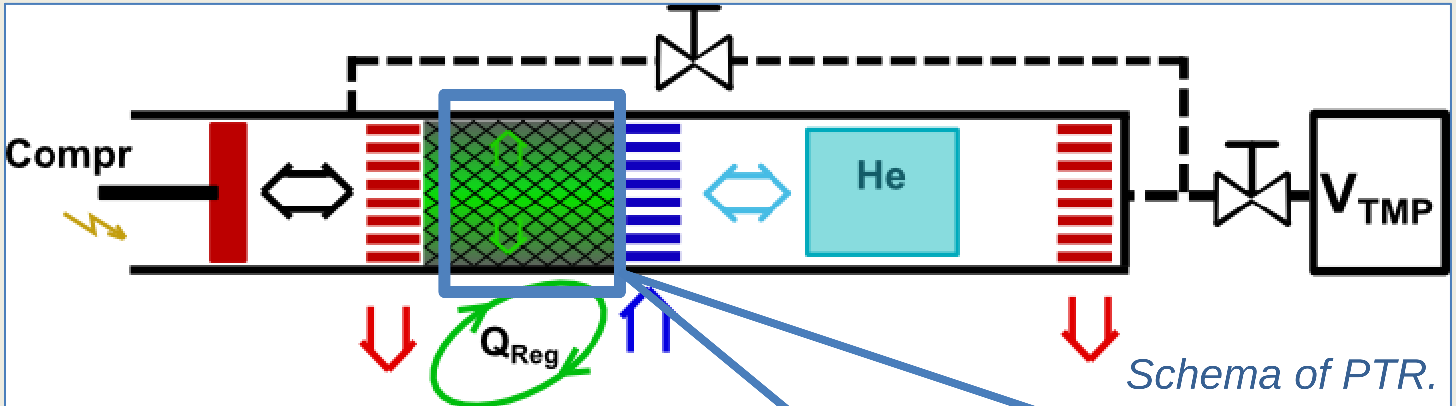
Conclusion et perspectives.

Regenerator matrix



Schema of PTR.

Regenerators are employed in Pulse Tube Refrigerators (**PTR**) or Stirling cycle machines. Its matrix is often composed of

a) Superposed metallic lattices(Ø30-110 µm) further called wound woven matrix.

b) metallic spheres (Ø300 µm).

$$\textbf{Regen. Performance} = \frac{\textbf{Heat transfer}}{\textbf{Pressure losses}}$$

a) **b)**

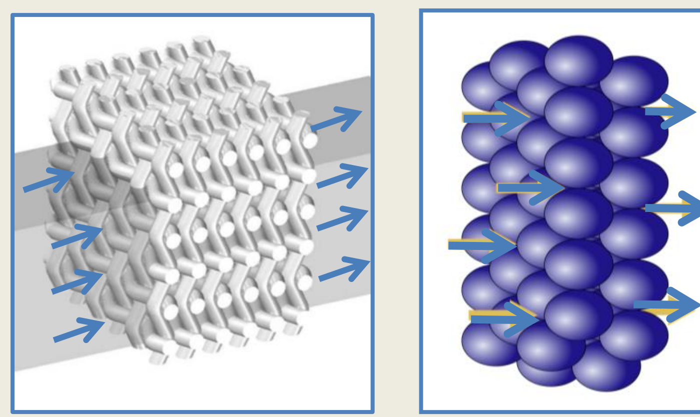


*Fig. Costa(2013)**

Costa(2013) – Costa S., Barrutia H., Esnaola J., Tutar M. Numerical study of pressure drop phenomena in wound woven matrix of Stirling regenerator. Energy conversion and management. 2013.

Hydrodynamic pressure losses in traditional regenerator matrix

Friction factor *f* (Darcy-Weisbach) describes **pressure drop losses (ΔP)** in regenerator matrices.

Ergun(1952) gave general empirical correlation for friction factor *f* for stationary laminar flow in porous matrix:

$$f = 133 \cdot Re^{-1} + 2{,}33$$

Gedeon(1996) experimentally obtained *f* for stationary flow through the Regenerator's wound woven matrix (fig.) composed of metallic wires Ø53µm with porosity $\varepsilon = 62\%$:

$$f = 129 \cdot Re^{-1} + 2{,}91 \cdot Re^{-0{,}103}$$

$$1 < Re < 6000$$

Costa(2013) numerically obtained *f* for stationary flow through the Regen. wound woven matrix (fig.) of Ø80-110µm and $\varepsilon = 47$ - 64%.

$$f = 123 \cdot Re^{-1} + 3{,}2 \cdot Re^{-0{,}104}$$

$$10 < Re < 400$$

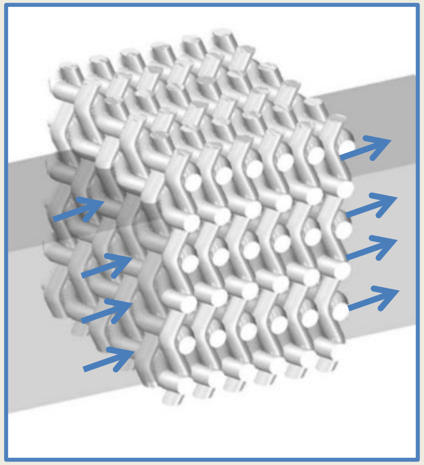


*Fig. Wound woven matrix of Stirling **regenerator** - Costa(2013)*

Optimisation and miniaturisation is complicated!

Hydrodynamic pressure losses in micro-machined regenerator matrix

a)
b)
c)

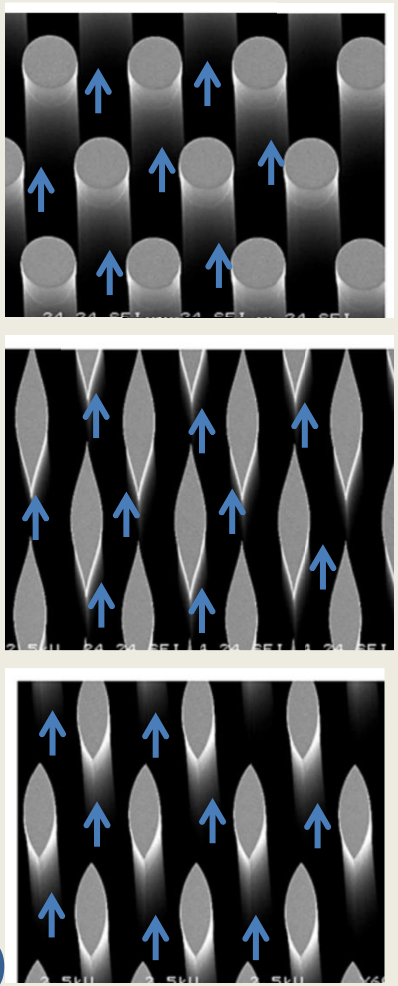
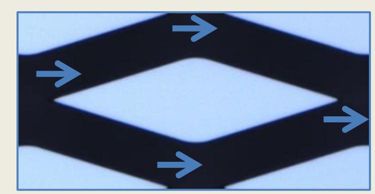


*Fig. Vanapalli (2007)**

Vanapalli(2007)* studied the influence of form on a hydraulic pressure losses in a matrice of pillars etched in Si wafer. **Porosity** was fixed to ε = **75%** and **aspect ratio** ξ of opening width e and etching depth h close to ξ =*e*/*h*=0,1 .

a) Circles	$f = 103,5 \cdot Re^{-0,44}$	
b) Sinusoidal	$f = 29,65 \cdot Re^{-0,94}$	Quite optimistic!
c) Eye	$f = 87,10 \cdot Re^{-0,80}$	
d) Rhomboid	$f = 175,20 \cdot Re^{-0,94}$	

Objective for our study is to show influence of porosity ε on f micro-machined regenerator matrices.



d)

***Vanapalli(2007) – Vanapalli S.,ter Brake H., Jansen H., et al. Pressure drop of laminar gas flow in a microchannel containing various pillar matrices . J. Micromech.Microeng. 2007.**

Dimensional analysis

Friction factor with :
U_m - *mean velocity.*

$$f = \frac{\Delta P}{\frac{1}{2}\rho \cdot U_m^2}\frac{D_h}{L_L}$$

Reynolds numbers 1<Re<100:

$$Re = \frac{U_m \cdot D_h}{\mu/\rho}$$

Hydraulic diameter with: S_{cont} - wetted surface , l_p - *wetted perimeter,*
h – etching depth.

Porosity:

$$\varepsilon = \frac{L_L \cdot L_T - a \cdot b}{L_L \cdot L_T}$$

$$D_h = \frac{4\varepsilon V}{S_{cont}} = \frac{4\varepsilon \cdot L_L \cdot L_T \cdot h}{2l_p \cdot h + 2\varepsilon \cdot L_L \cdot L_T}$$

Length/width ratio of rhombus:

$$\alpha = atan\left(\frac{a}{b}\right) = 33^\circ$$

Aspect ratio ξ (for 2D ξ ->0):

$$\xi = \frac{e}{h} \sim \frac{2 \cdot L_L \cdot L_T \cdot \varepsilon}{2 \cdot l_p \cdot h}$$

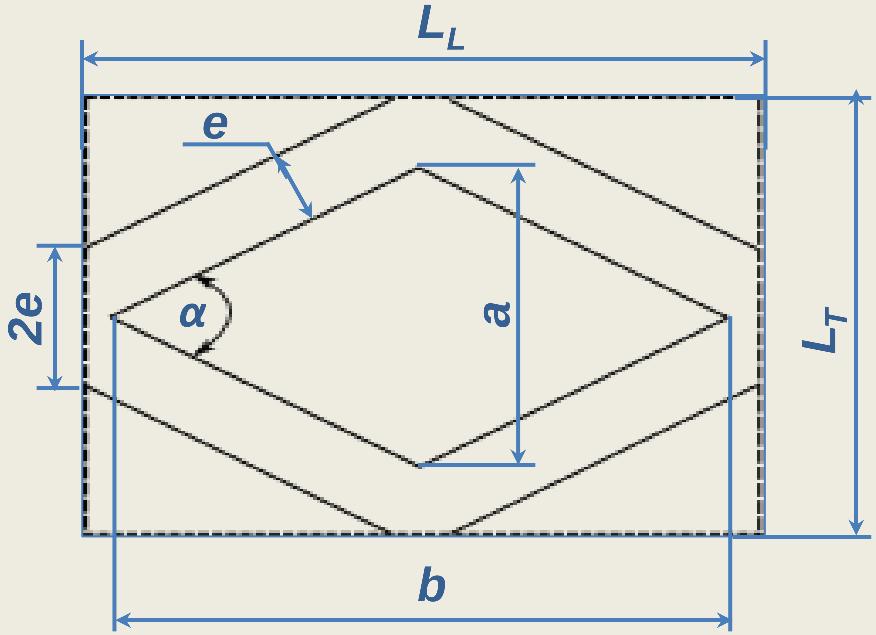


Fig. ***REV*** *– Representative Elementary Volume .*

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Direct Numerical Simulation (DNS)

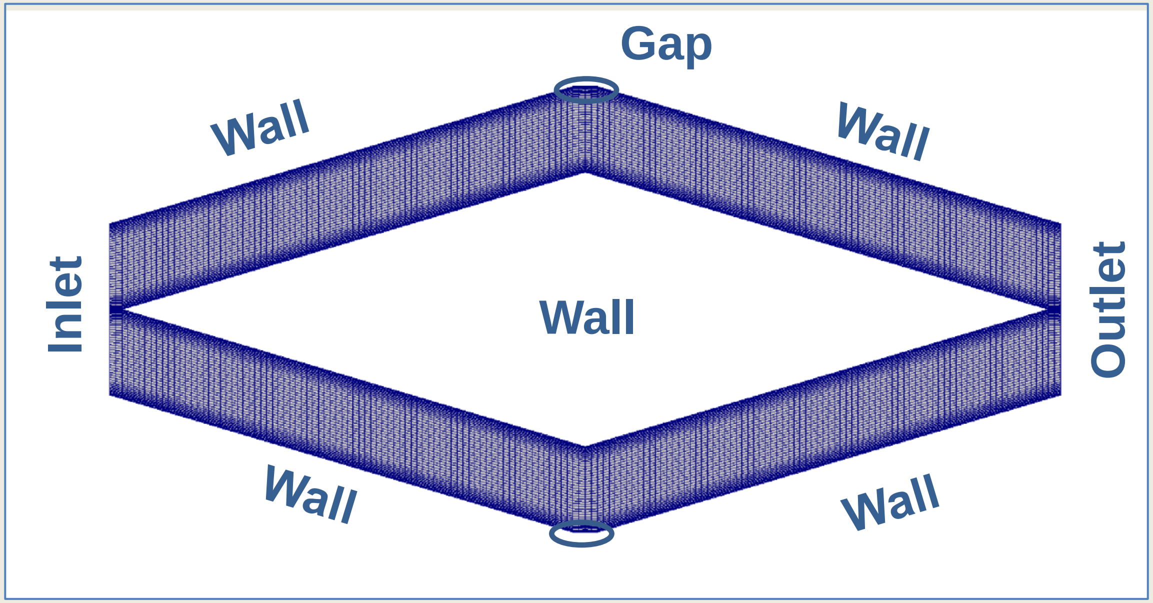
Equations for stationary incompressible flow:

$$\begin{cases} \nabla \cdot U = 0 \\ (\nabla \cdot U)U = -\nabla \cdot p + \vartheta \cdot \nabla^2 \cdot U \end{cases} \quad \text{avec} \quad \vartheta = \frac{\mu}{\rho}$$

OpenFOAM Solver:

simpleFoam (laminar)

Linear pressure gradient is imposed to settle the flow.

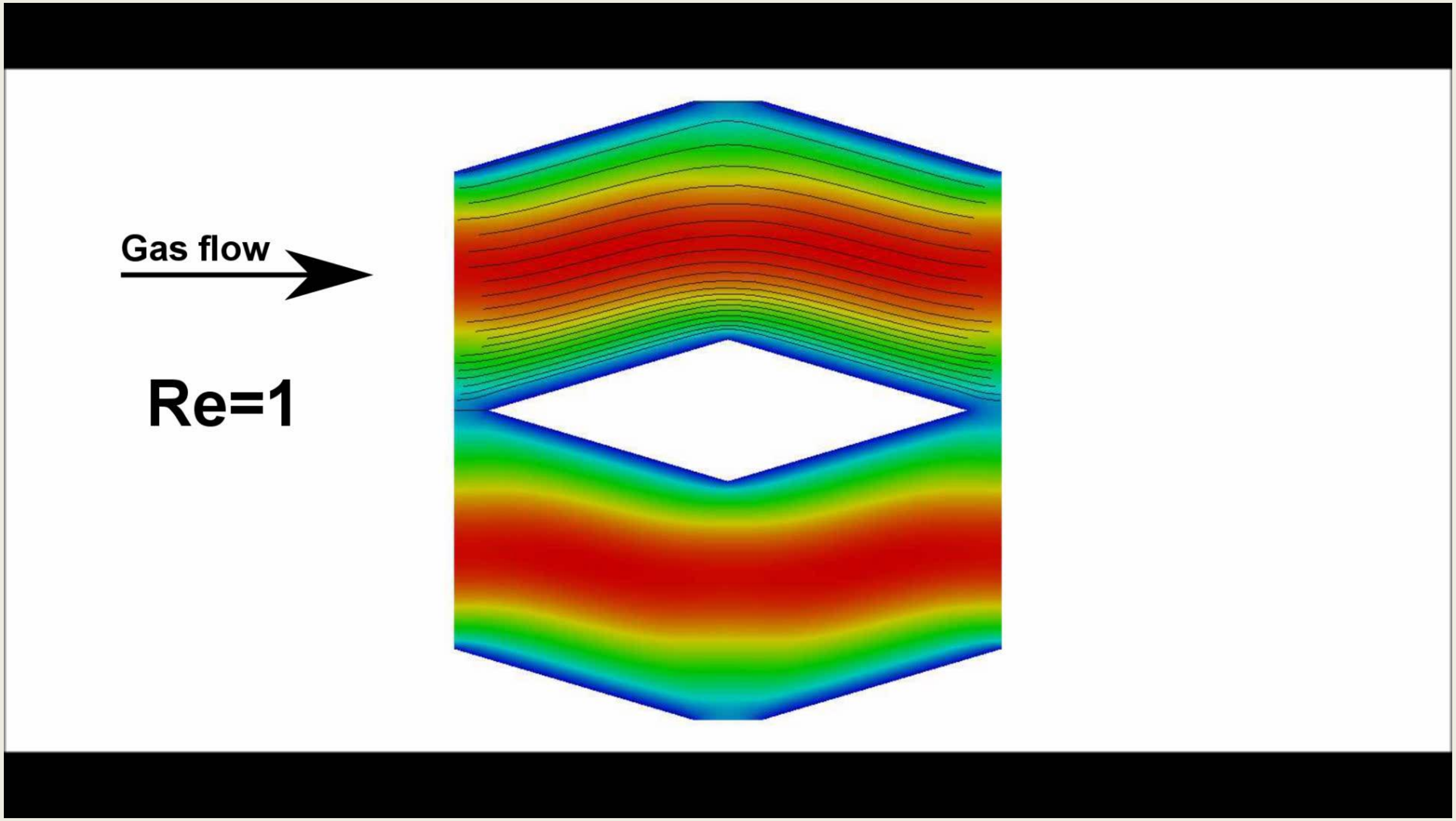


Boundary Conditions (BC):

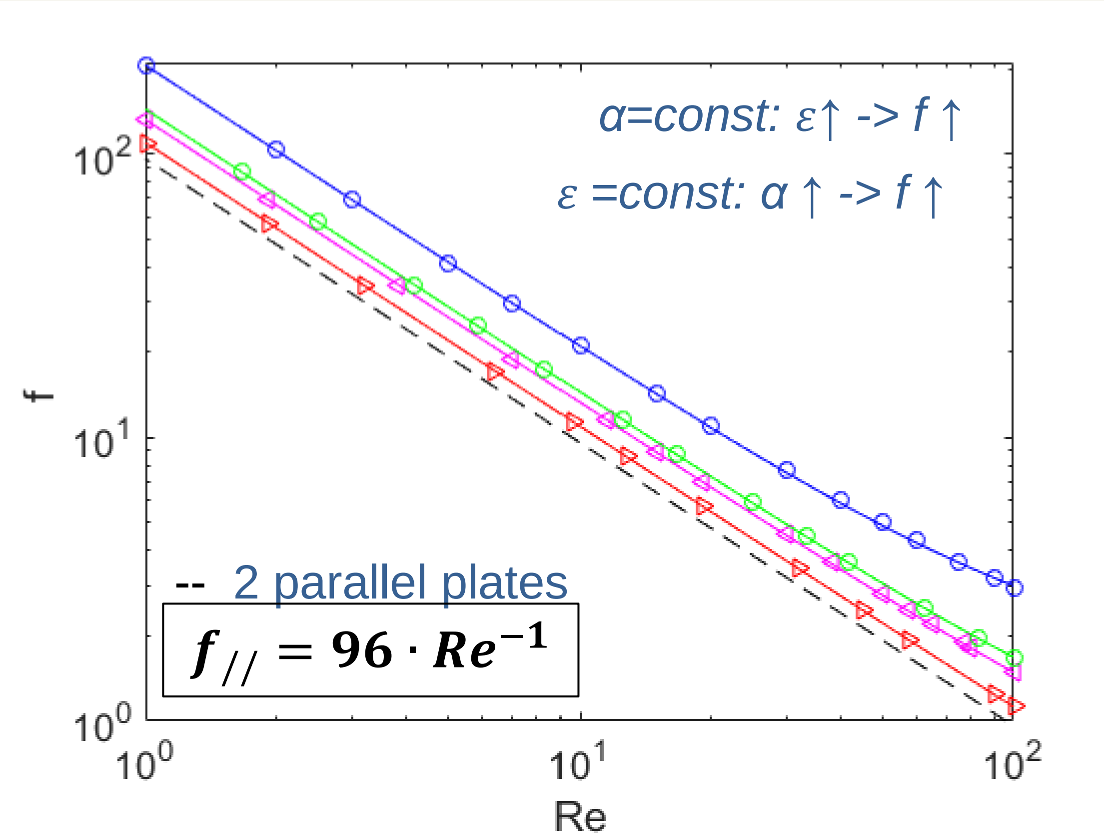
- **Inlet/Outlet: "cyclic" for pressure p and velocity U(x,y).**
- **Walls: U(wall)=0.**
- **Gap: "Symmetry plane "**

*Fig. Mesh example for REV with **α=33°, ε** = 40% and **BC** imposed.*

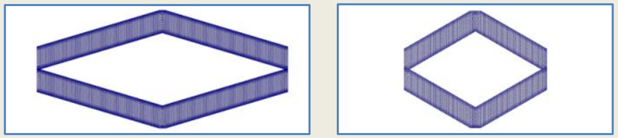
Velocity field U(x,y) for different Re DNS for REV α=33°, ε=80%



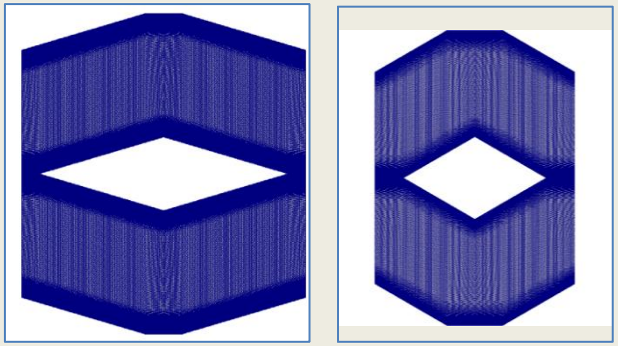
DNS friction factor f for REV with α=33° and 60°



α=33°, ε =40%, α=60°



α=33°, ε = 80%, α=60°



▷ α=33°, ε = 40%

$$f_{\alpha=33°,40\%} = 109,6 \cdot Re^{-1}$$

◁ α=33°, ε = 80%

$$f_{\alpha=33°,80\%} = 132,0 \cdot Re^{-1} \cdot \left(1 + 2,5 \cdot 10^{-4} \cdot Re^{-1,4}\right)$$

○ α=60°, ε =40%

$$f_{\alpha60°,\ 40\%} = 143,7 \cdot Re^{-1}\left(1 + 2,2 \cdot 10^{-4} \cdot Re^{-1,4}\right)$$

○ α=60°, ε = 80%

$$f_{\alpha60°,80\%} = 205,2 \cdot Re^{-1}\left(1 + 12,0 \cdot 10^{-4} \cdot Re^{-1,3}\right)$$

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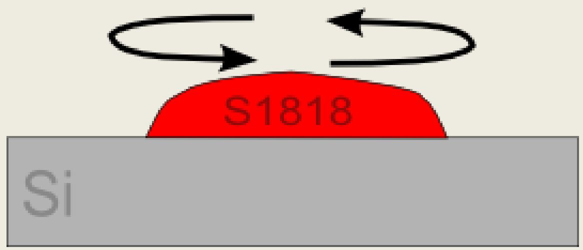
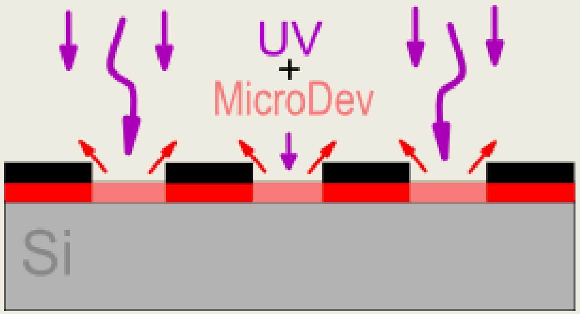
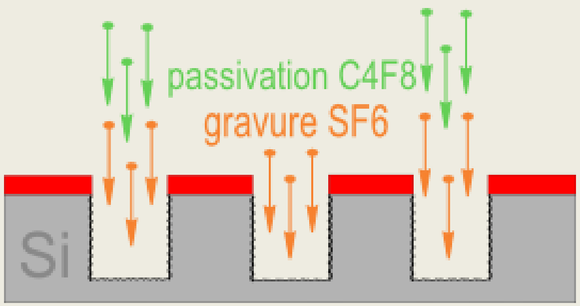
Micro-machining of Regenerator

1. Lithography of UV polymer (S1818 or AZ4562).

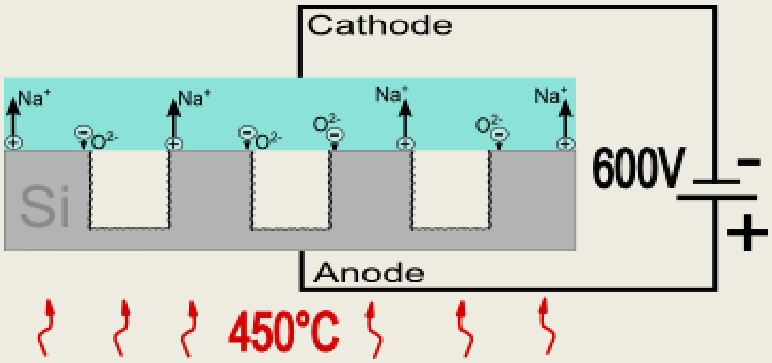




2. Deep Reactive Ion Etching DRIE (h=100-250µm).



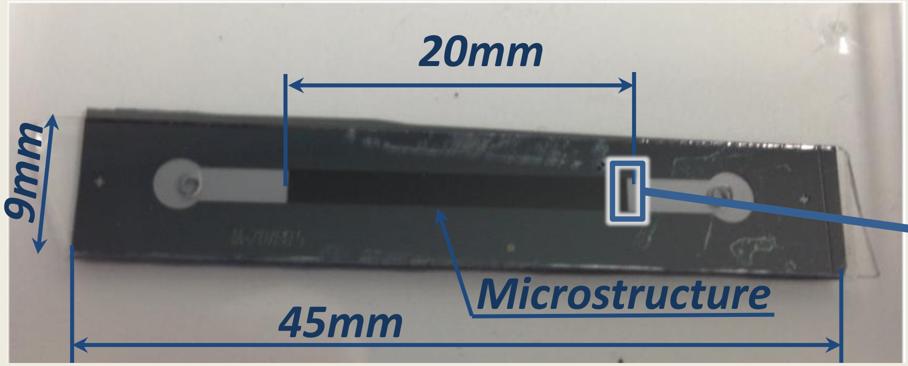
3. Anodic bonding with Pyrex.



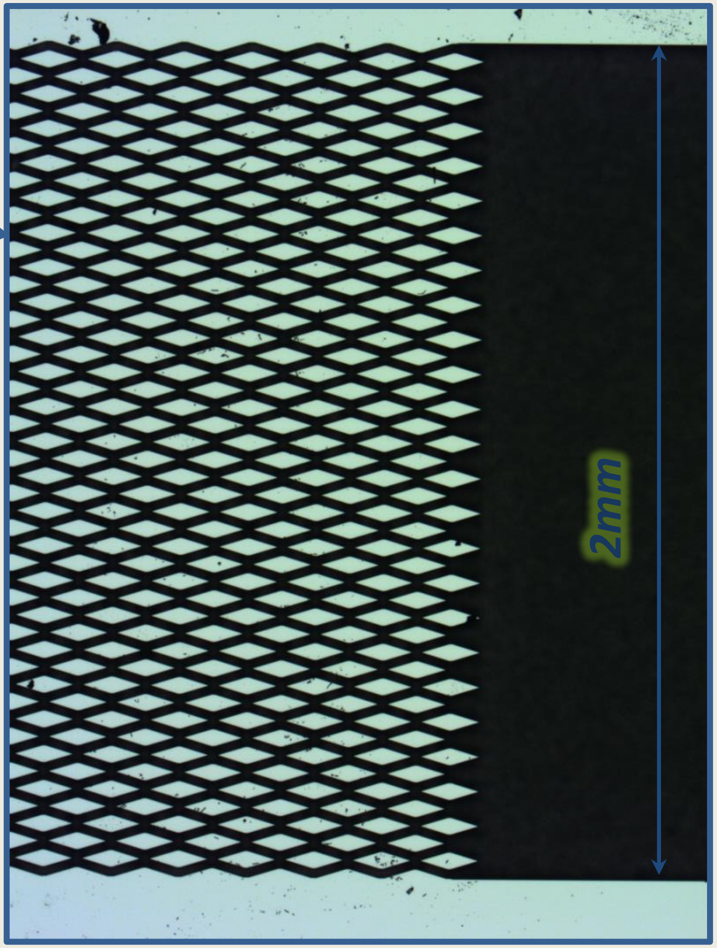
Clean rooms:

- Plateforme Technologique Amont. - NanoFab, Institut Néel.

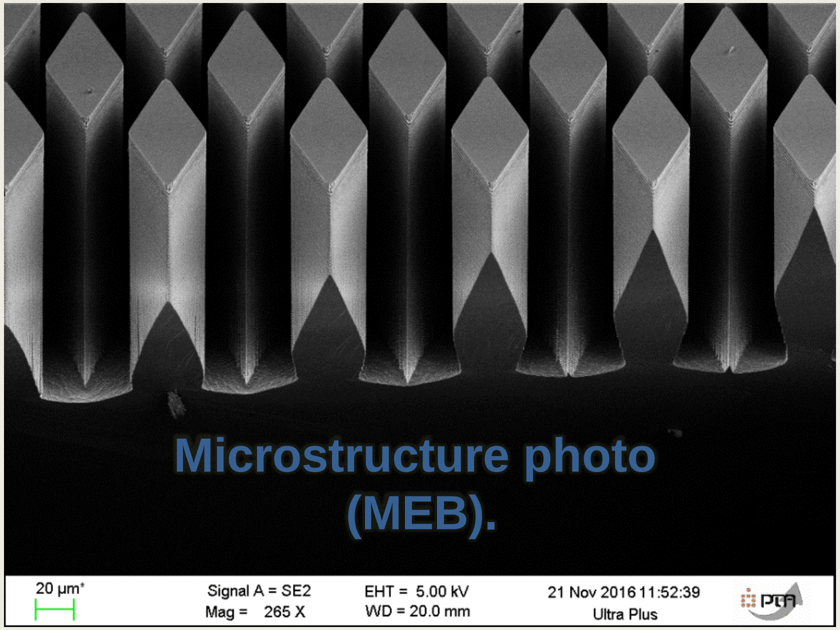
Microstructure of regenerator



Regenerator's sample photo.



The photo of microstructure.



Microstructure photo (MEB).

Experimental test setup

P_in, P_out : pressure gauges.

Tc_in, Tc_out : thermocouples.

Q – flowmeter.

Vtmp – buffer volume.

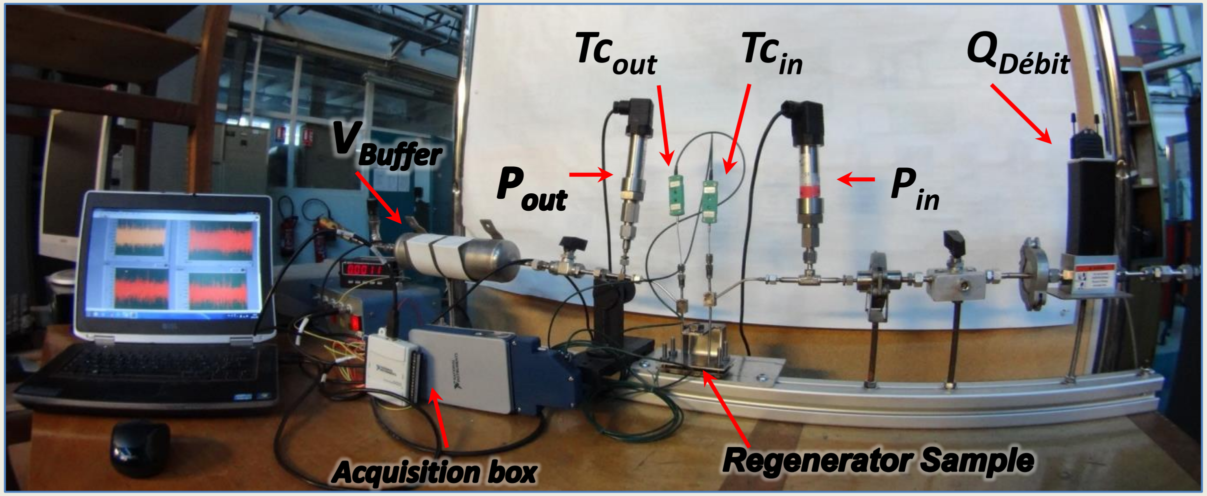


Fig. Photo of expérimental setup .

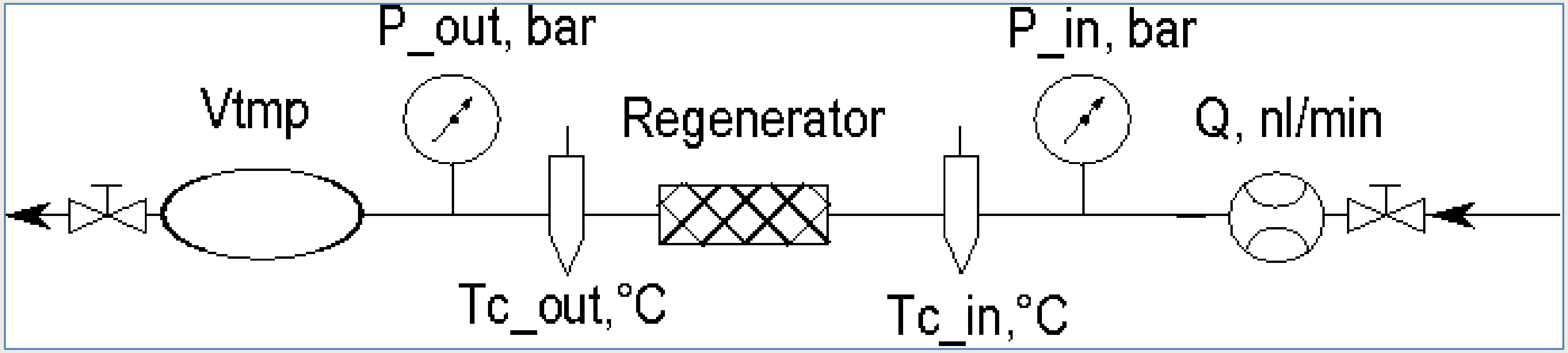
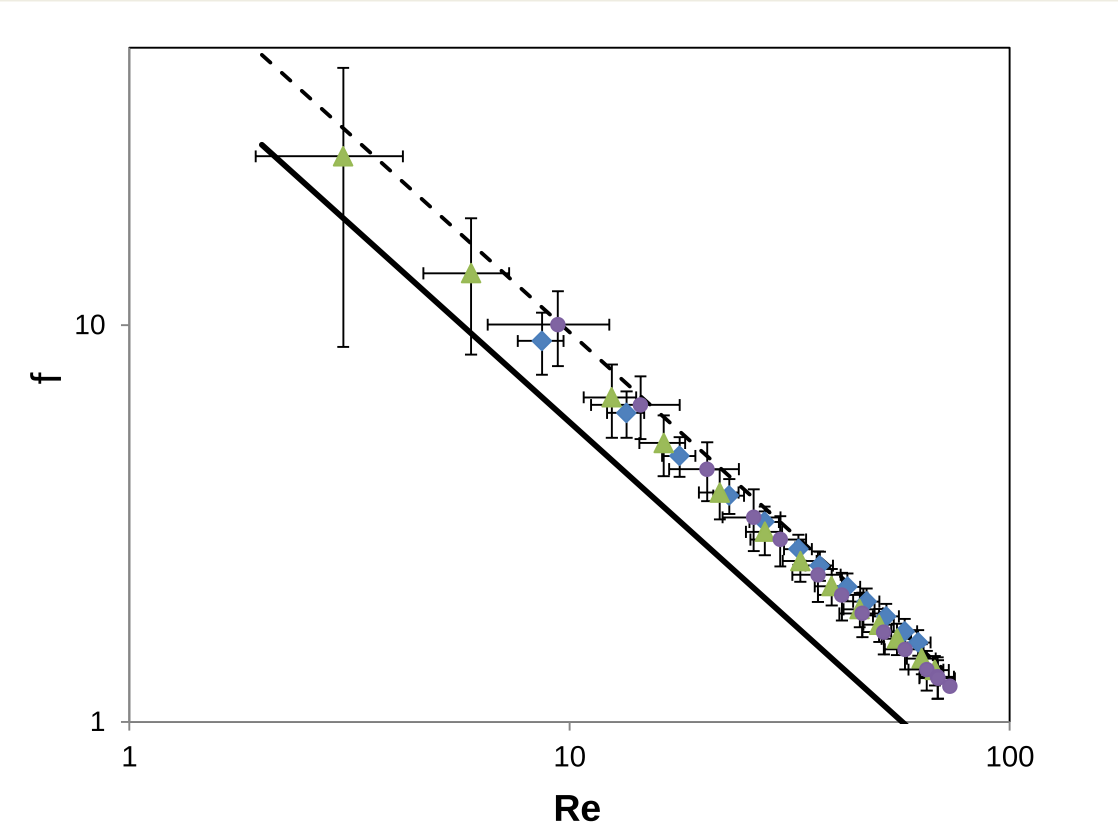


Fig. Schema for experimental measurements .

Confirmation of experimental setup by test of empty channels



▲ Canal_KOH02, h=22,4µm ξ=0,011, D_h=44,3µm

$$f_{Can\_KOH2} = 84,4 \cdot Re^{-1}$$

● Canal_KOH03, h=31,4µm, ξ =0,016, D_h=61,3µm

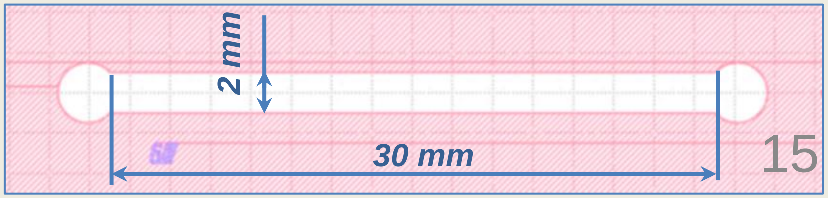
$$f_{Can\_KOH3} = 87,2 \cdot Re^{-1}$$

◆ Canal_KOH04, h=17,2µm, ξ=0,009, D_h=33,9µm

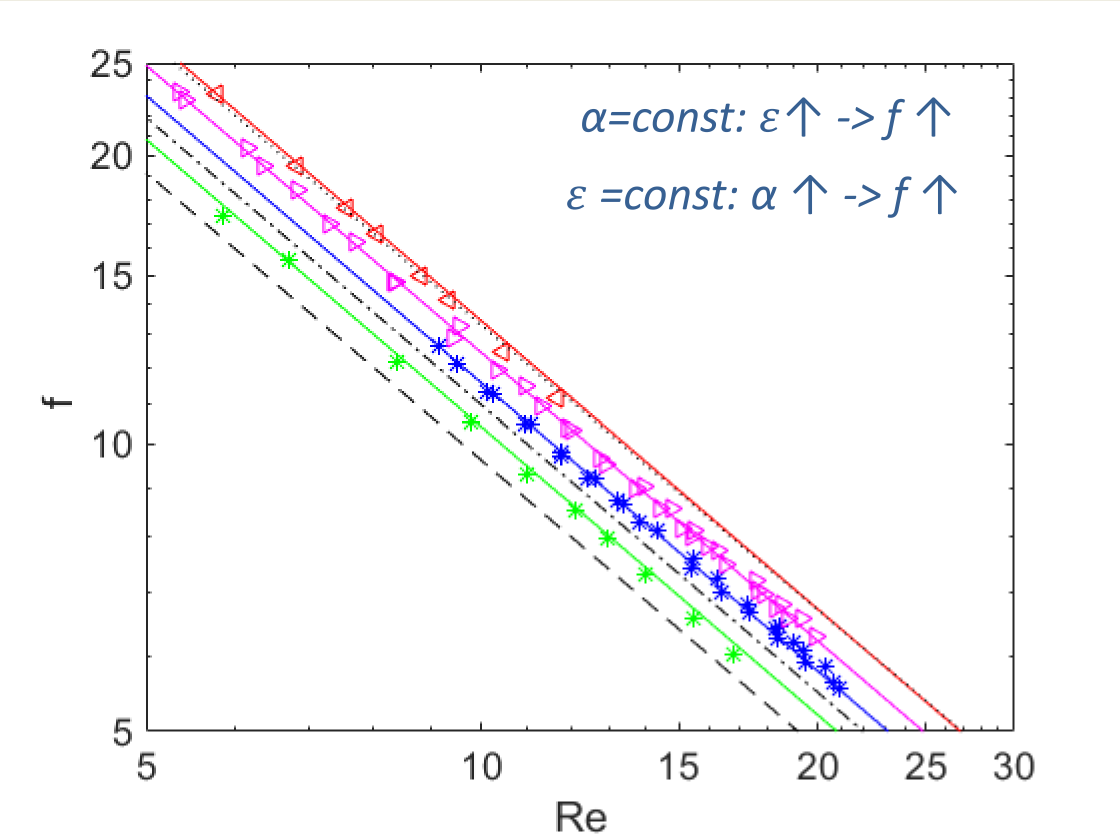
$$f_{Can\_KOH4} = 88,1 \cdot Re^{-1}$$

– Square channel ξ=1 $$f_{\blacksquare} = 56,96 \cdot Re^{-1}$$

-- 2 parallel plates ξ=0 $$f_{//} = 96 \cdot Re^{-1}$$



Experimental study of regenerator's matrices with α=33°and e=20µm



* Regen2_DRIE13,
ε=41,7%, ξ=0,099, D_h=43,3µm

$$f_{Reg2\_DR13} = 104,0 \cdot Re^{-1}$$

* Regen2_DRIE05,
ε = 45,1%, ξ=0,178, D_h=45,2µm

$$f_{Reg2\_DR05} = 115,6 \cdot Re^{-1}$$

▷ Regen3_DRIE12,
ε=65,2%, ξ =0,193, D_h=45,3µm

$$f_{Reg3\_DR12} = 124,3 \cdot Re^{-1}$$

◁ Regen3_DRIE13,
ε =61,8%, ξ=0,102, D_h=44,9µm

$$f_{Reg3\_DR13} = 134,2 \cdot Re^{-1}$$

-- 2 parallel plates

$$f_{//} = 96 \cdot Re^{-1}$$

-·- DNS ε =40%, ξ=0.

$$f_{\alpha=33°,40\%} = 109,6 \cdot Re^{-1}$$

··· DNS ε =80%, ξ=0.

$$f_{\alpha=33°,80\%} = 132,0 \cdot Re^{-1}$$

Conclusion

<u>Conclusion:</u>

- **The influence of porosity *ε* is shown numerically and confirmed experimentally. For identical pillars, matrices with lower porosity have lower friction factor. *α=const: ε*↑ -> *f* ↑**

- **For fixed porosity *ε*, matrices composed of pillars with lower angle *α* have lower friction factor. *ε =const: α* ↑ -> *f* ↑**

- **The limits for friction factor *f* in micro-machined matrix are given by two parallel flat plates (*f*=96/Re) for aspect ratios *ξ* ->0 and square channel (*f*=56,96/Re) for *ξ*->1 .**

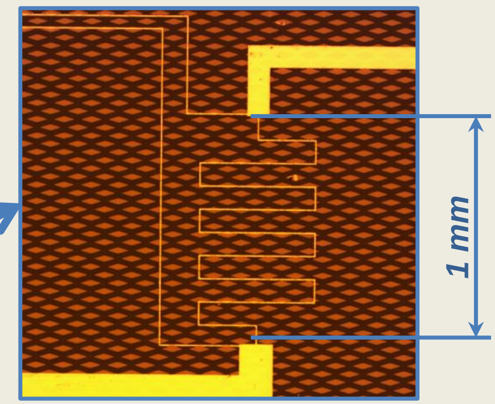
- **Friction factor *f* of micro-machined regenerator's matrices with *α=33° and porosities ε <70%* seems to be favorable comparing with wound woven matrices (superposed metallic wire lattices).**

Perspectives

<u>Perspectives:</u>

- Implantation of resistance thermometers inside the regenerator's matrix to study the heat transfer efficiency (Nusselt number) and its dependence on porosity and pillars shape.

- Passive module of PTR etched in Si.



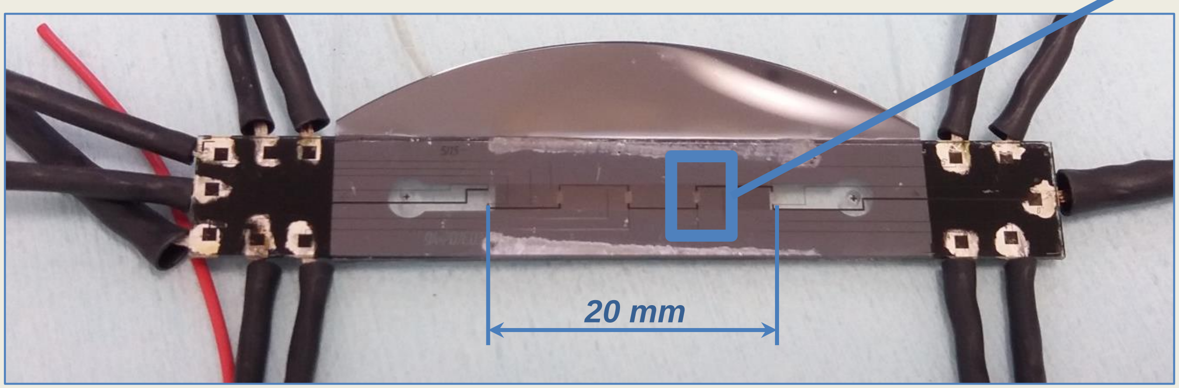


fig. Photo of micro-machined regenerator's sample equipped by thermometer .

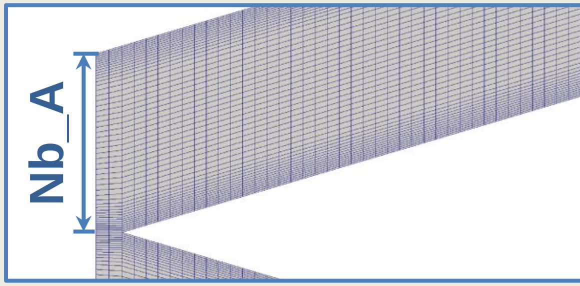
Thank you
for your attention!

Contact speaker: Arkadii.Sochinskii@univ-grenoble-alpes.fr

Acknowledgments:

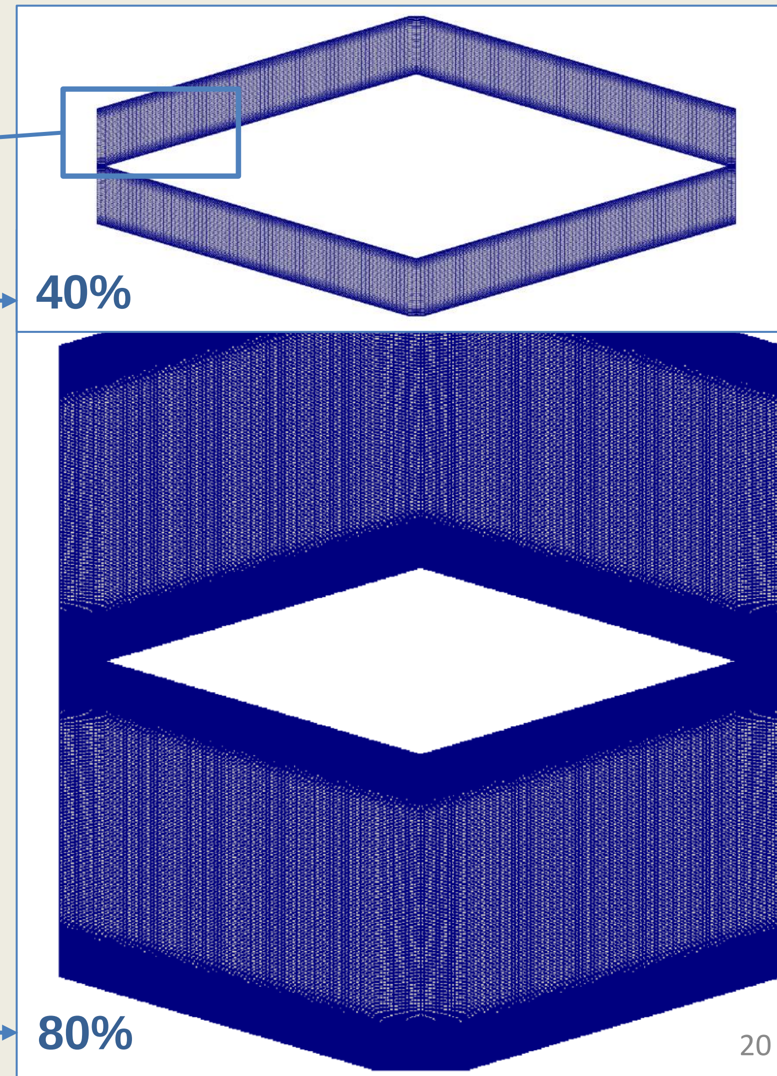
Labex LANEF for funding of this PhD research.

Annexe 1: Meshing.



Mesh characteristics for *α=33°*
(number of finite volumes VF):

Mesh	Total FV	Nb_A
ε=40%	*16400*	50
ε=50%	23520	70
ε=60%	35200	100
ε=70%	64800	180
ε=80%	96000	250
ε=90%	139200	300



Anexe2: Experimental analysis for matrices with α=33°; ε=40,60%; 1<Re<60.

DNS ε =**40%**,ξ=0 $f_{40\%} = 109,6 \cdot Re^{-1}$

DNS ε =**60%**, ξ=0 $f_{60\%} = 115,2 \cdot Re^{-1}$

e=20μm

Reg2_DR13,ξ=0,099, **ε=41,7%**, D_h=43,3μm $f = 104,0 \cdot Re^{-1}$

Reg3_DR13,ξ=0,102, **ε =61,8%**, D_h=44,9μm $f = 134,2 \cdot Re^{-1}$

Reg2_DR05, ξ=0,178, **ε = 45,1%**, D_h=45,2μm $f = 115,6 \cdot Re^{-1}$

Reg3_DR12,ξ =0,193, **ε=65,2%**, D_h=45,3μm $f = 124,3 \cdot Re^{-1}$

e=40μm

Reg4_DR05,ξ=0,290 **ε = 42,0%**, D_h=73,4μm $f = 103,9 \cdot Re^{-1}$

Reg5_DR05,ξ =0,314, **ε=63,8%**, D_h=77,8μm $f = 124,2 \cdot Re^{-1}$

Reg5_DR12, ξ=0,333, **ε =62,0%**, D_h=72,8μm $f = 133,3 \cdot Re^{-1}$

Reg7_DR05, ξ=0,115, **ε=45,1%**, D_h=29,5μm $f = 107,6 \cdot Re^{-1}$

e=10μm

Reg7_DR13,ξ=0,088, **ε = 46,0%**,D_h=26,4μm $f = 113,7 \cdot Re^{-1}$

Reg8_DR05,ξ =0,131, **ε=65,2%**, D_h=33,2μm $f = 116,4 \cdot Re^{-1}$

DNS ε =**50%**,ξ=0 $f_{50\%} = 111,6 \cdot Re^{-1}$

DNS ε =**70%**, ξ=0 $f_{70\%} = 121,0 \cdot Re^{-1}$