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LATTICE STRUCTURE IN HEAT EXCHANGERS

Design for additive manufacturing

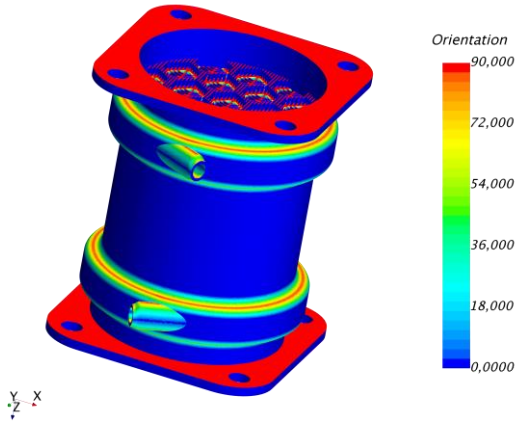
Jean-Michel HUGO

contact@temisth.com

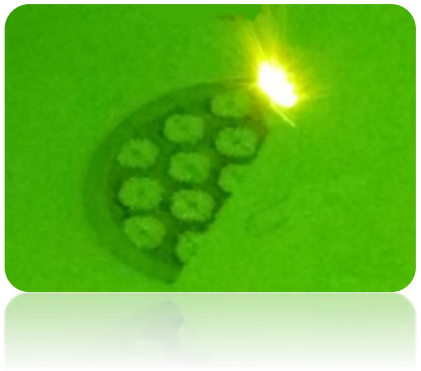
www.temisth.com

+33 6 78 84 97 98

Introduction



3D file



Additive Manufacturing

Real part

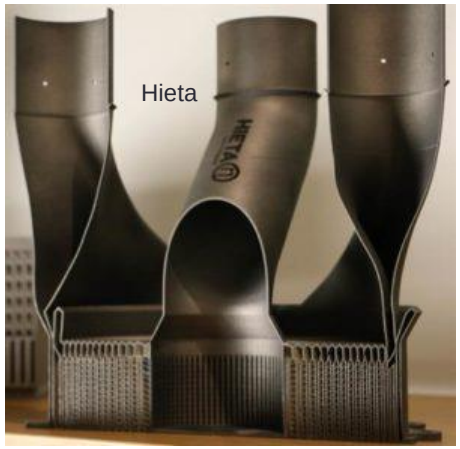
From virtual file to a materialized component

Allow realizing complex porous structures

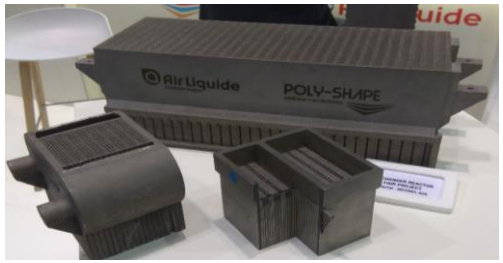
Allow reducing assembly

Parts can be modified and produced on demand

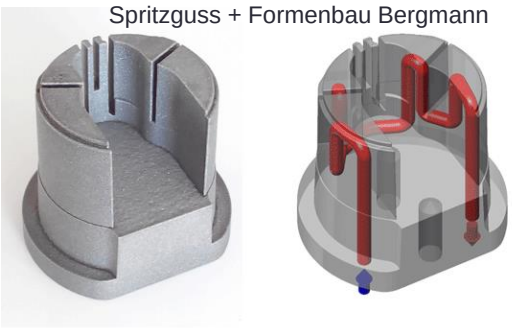
Domains of application



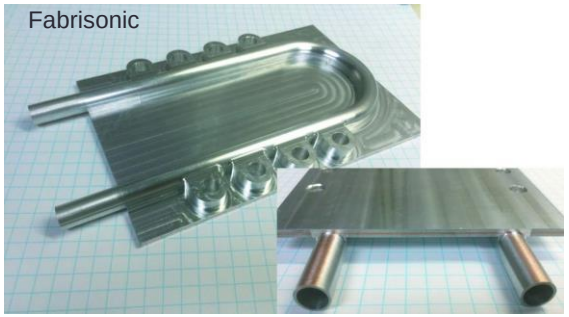
Automotive application



Oil & Gas



Conformal cooling



Cold Plate & heat pipe

Aircraft

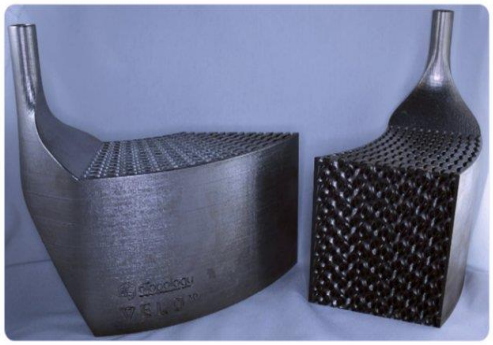
Etc.

With AM, a better integration

- Integration of heat exchanger in engine casing
  - Classical heat exchanger are cubic
  - Aircraft engines present curved shape

United Technology Corp.

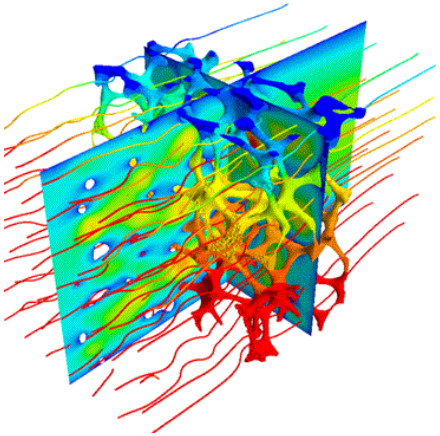
PrintSky & Temisth



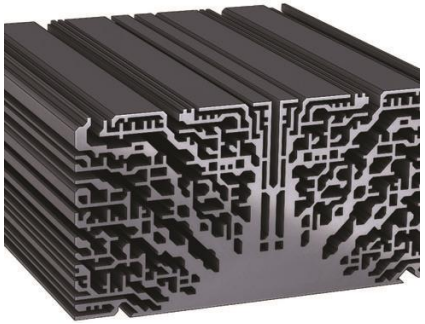
Velo3D & nTopology

- Reducing part assembly and part welded
- Coupling functions
- Using and existing mechanical parts

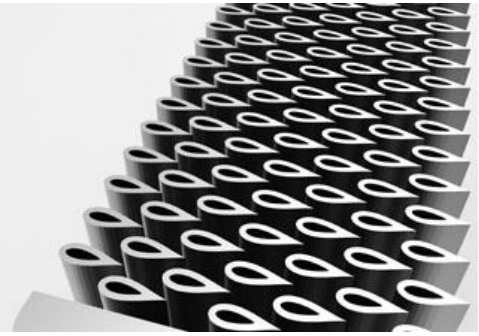
Optimized design with numerical tools



CFD &
FEA

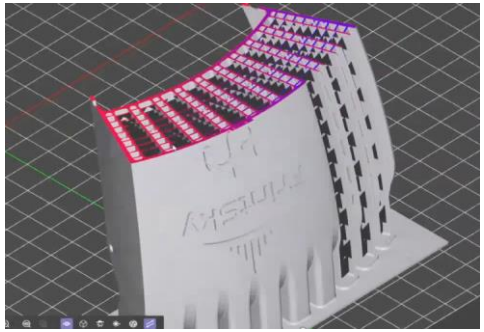


Topology
optimization



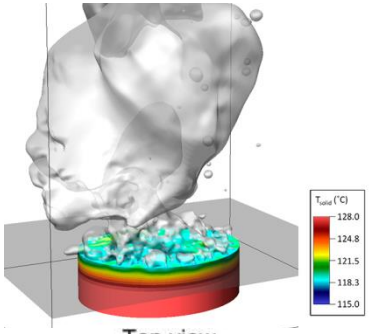
Parametric
optimization

- Thermal and fluid simulation
  - Adaptative geometry to physical phenomenon
- Weight reduction
- Ensuring the fabrication : AM process simulation

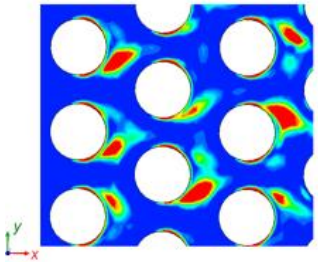


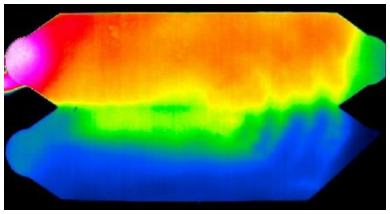
Manufacturing
simulation

Complexity of models



Top view
(cross-section volume fraction)





Local

All the physics
ROI : small channel

Mezzo

Simplified physics
ROI : representative channel

Macro

Equivalent model
ROI : entire heat exchanger

0D

Correlations
ROI : one heat exchanger

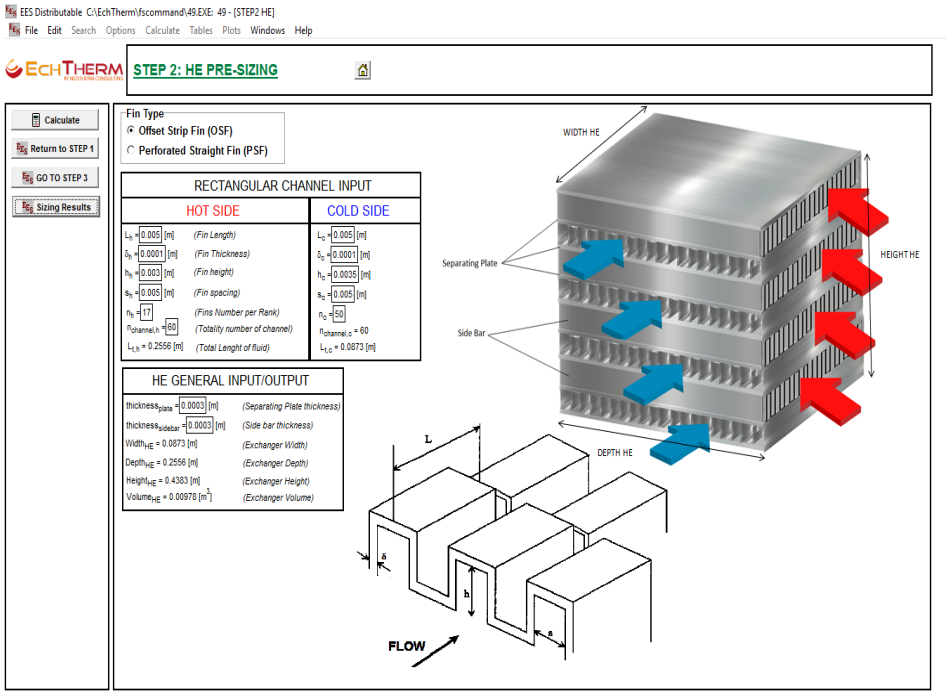
Classical heat exchanger design

Heat exchanger design and expertizing using **EchTherm** software from Neotherm Plate and fins

- Tubes and fins
- Boiler …

Pre-sizing :

- Volume (Depth, Heigth, width) and mass
- Performances prediction (Thermal efficiency and pressure drop)
- Numerical simulation



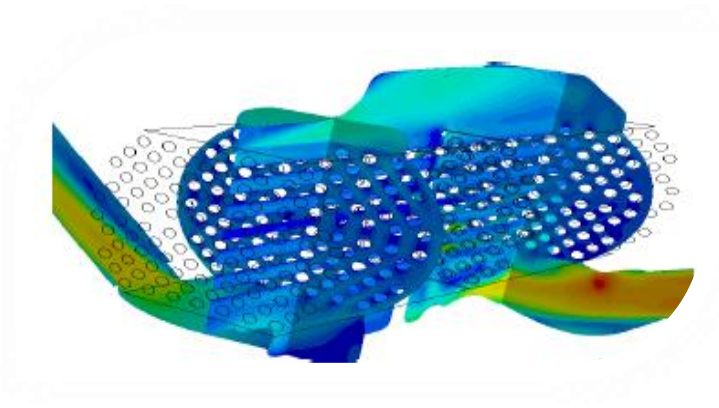
Based on NTU Method

Correlations data base

Use of CFD

Obtain 3D scalar fields (temperature, velocity, pressure etc.)
➔ better understanding of physical phenomena
Optimization design capabilities

- Fluid flow regulation – complete literrature correlation
- Parametric study
- Topological optimization



Heat exchanger are made of several parts

- Fins (thickness ~0,05 – 0,30mm)
- Fins pitch (~2,00mm)
- Tubes (diameter ~5-10mm / thickness ~0,50mm)
- Overall size : 100-1000 mm
- ➔ 100 tubes and fins with different scale
  ➔ Mesh size : over 100 millions cells

What about lattice structure ?

Metal foam heat exchangers

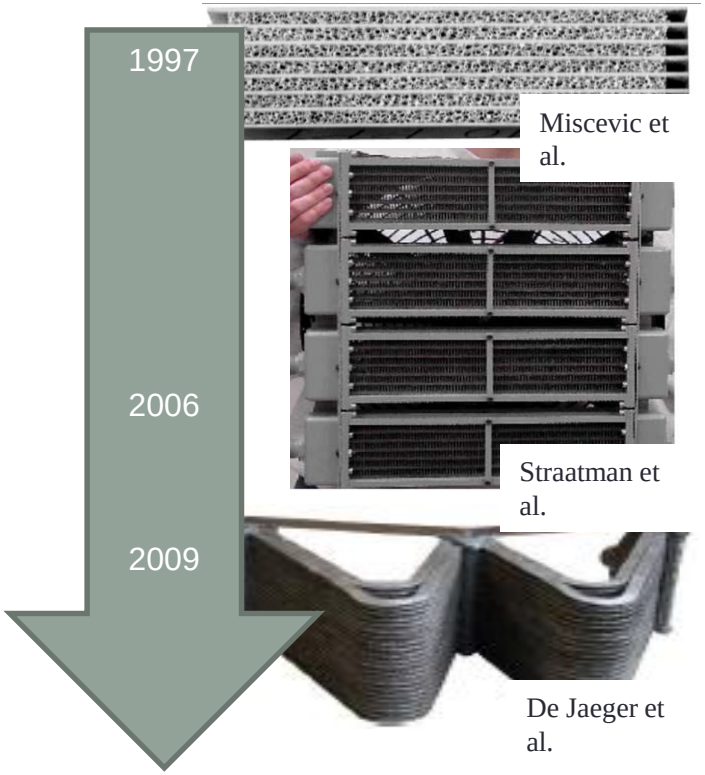
- High potential:
  - Low Reynolds number fluid flow
  - Gathering functions (energy absorption)
  - Liberty of design

- No industrialisation – only niche market

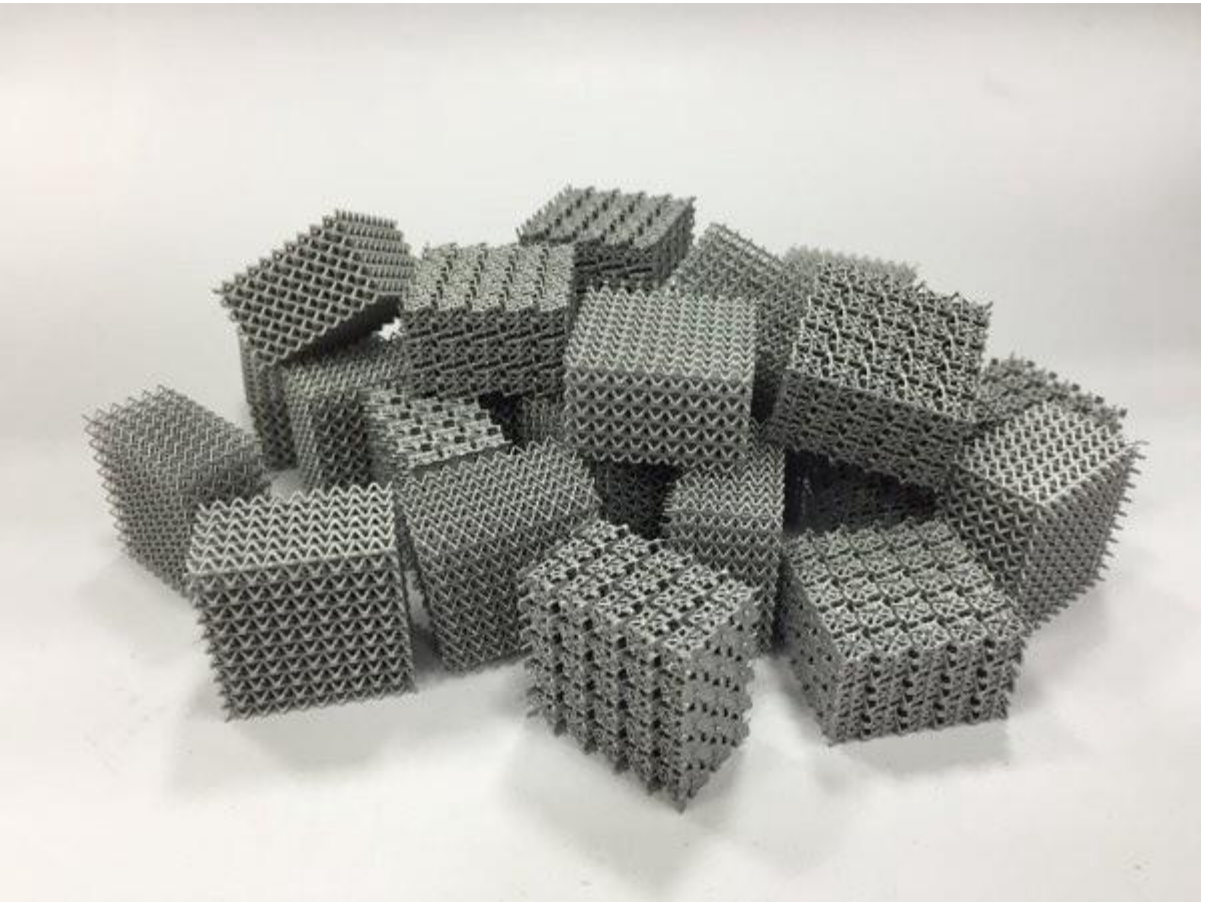
- Scientific issues: only few data on heat exchanger
  Only case study available
- Technical issue:
  - Link between foam and wall
  - Control of local porosity and geometric parameters

- A lot of correlation between
  moprhology and thermophysical porperties

➔ After 2009 : additive manufacturing appeared



Lattice structures vs. metal foams



https://medium.com/@revrandom/3d-printing-is-grid-locked-in-lattice-structures-fd9e053ee959

- A lot of lattice structures
- Only studied for mechanical applications
- Literature on metal foam can be used for additive manufacturing

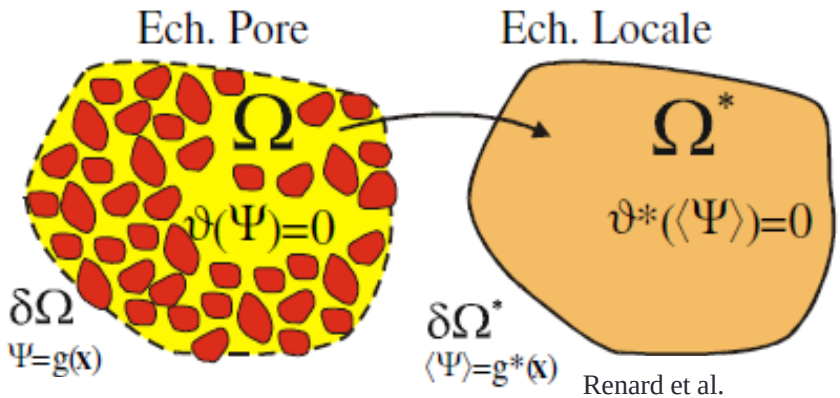
An equivalent porous approach for heat exchanger design

Volume averaging techniques

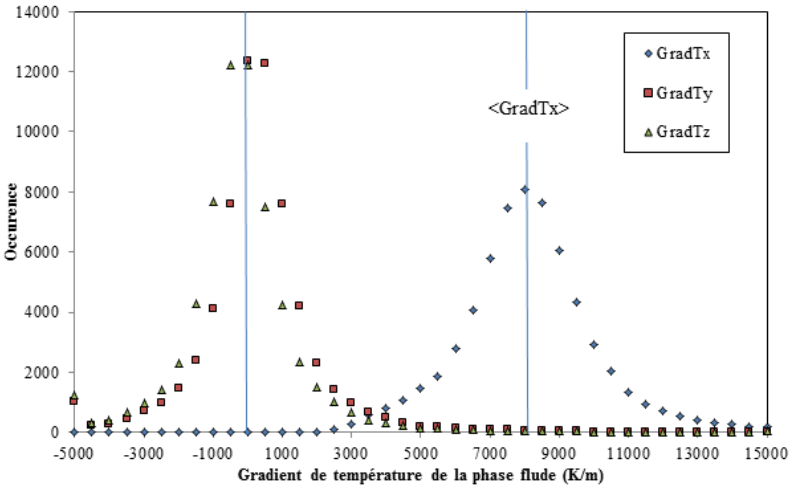
$$< \psi > = \frac{1}{V} \int_V \psi \, dV$$

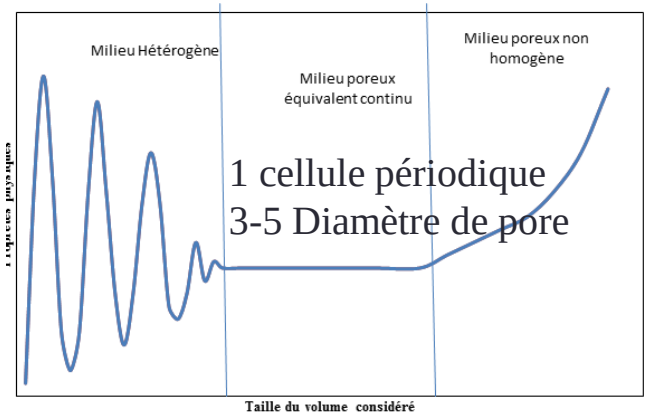
$$< \lambda_s \nabla T_s > = \lambda_s \left(\nabla < T_s > + \frac{1}{V} \int_A \mathbf{n_{sf}} \, T_s \, dA \right)$$

Volume averaging on REV



Renard et al. (2009).



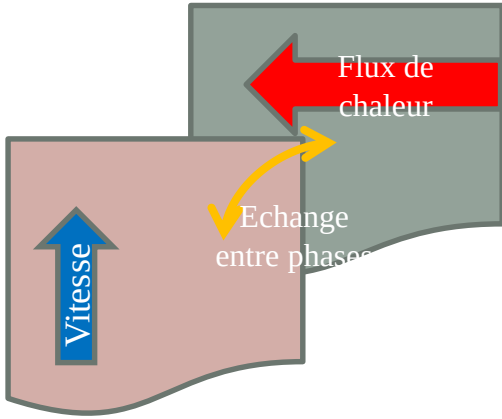


Heat exchangers can be represented by a porous medium

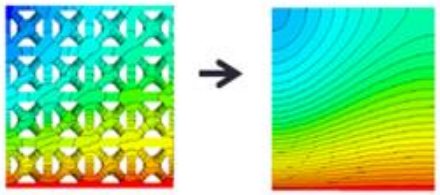
Non-equilibrium thermal model

Two temperatures model

$$\begin{cases} \varepsilon(\rho C_P)_f \dfrac{\partial T_f}{\partial t} + \varepsilon(\rho C_P)_f U.\nabla T_f = \nabla.\left(\lambda_f^{eff} \nabla T_f\right) + h\left(T_f - T_S\right) \\ (1-\varepsilon)(\rho C_P)_S \dfrac{\partial T_S}{\partial t} = \nabla.\left(\lambda_S^{eff} \nabla T_S\right) + h\left(T_S - T_f\right) \end{cases}$$



- Effective conductivity of solid phase
- Darcy-Forchheimer model for pressure loss
- Thermal non-equilibrium between phases : use of heat transfer coefficient
- Use of anisotropic media



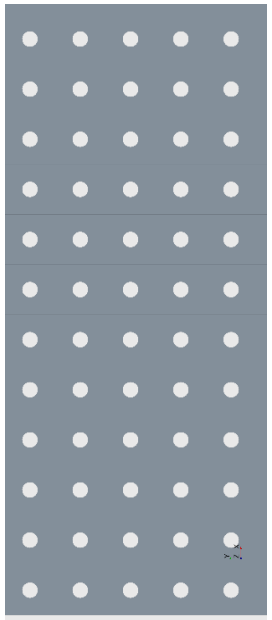
$$< \psi >= \overline{\overline{K_{eff}}}\, \nabla < H > \quad \text{avec} \quad \overline{\overline{K_{eff}}} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{xy} & K_{yy} & K_{yz} \\ K_{xz} & K_{yz} & K_{zz} \end{bmatrix}$$

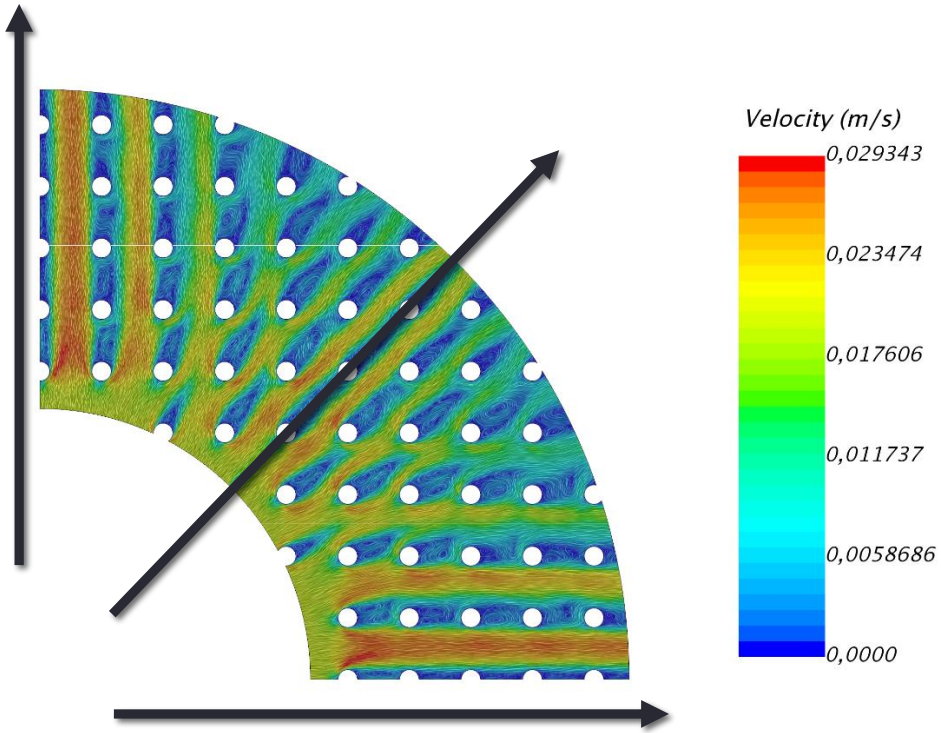
- Scalar field analysis
  - Averaged velocity, temperature, pressure…
- Possibility of evolutive structure

Fluid flow description

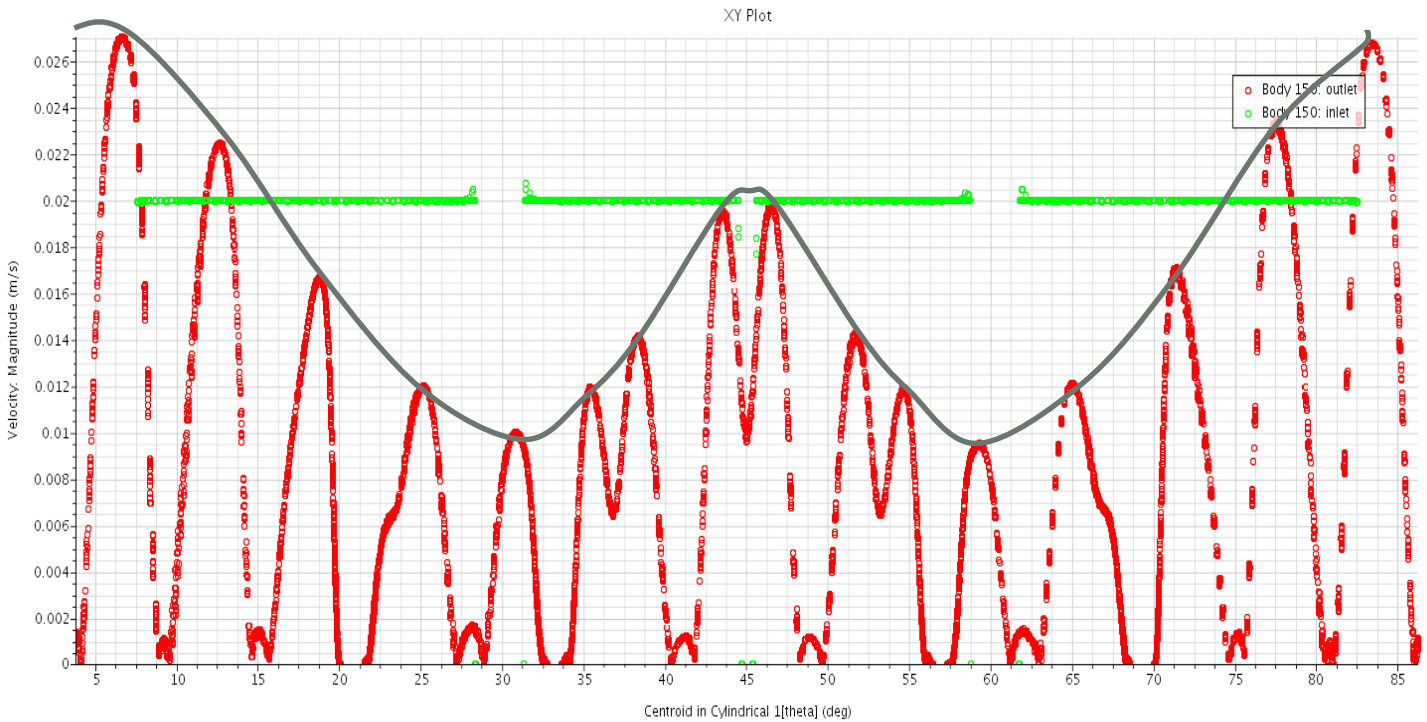
- Forchheimer law in cartesian basis

$$-\nabla \boldsymbol{P} = \frac{\mu}{K}\boldsymbol{U} + \rho\beta||\boldsymbol{U}||\boldsymbol{U} \qquad \overline{\overline{K^{-1}}} = \begin{bmatrix} Kxx & Kxy & Kxz \\ Kyx & Kyy & Kyz \\ Kzx & Kzy & Kzz \end{bmatrix}$$

- 



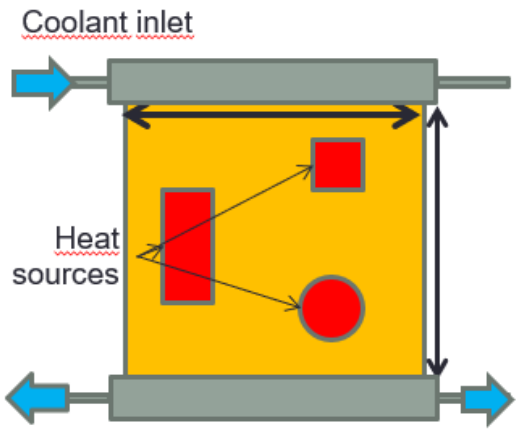
Polar coordinates systems



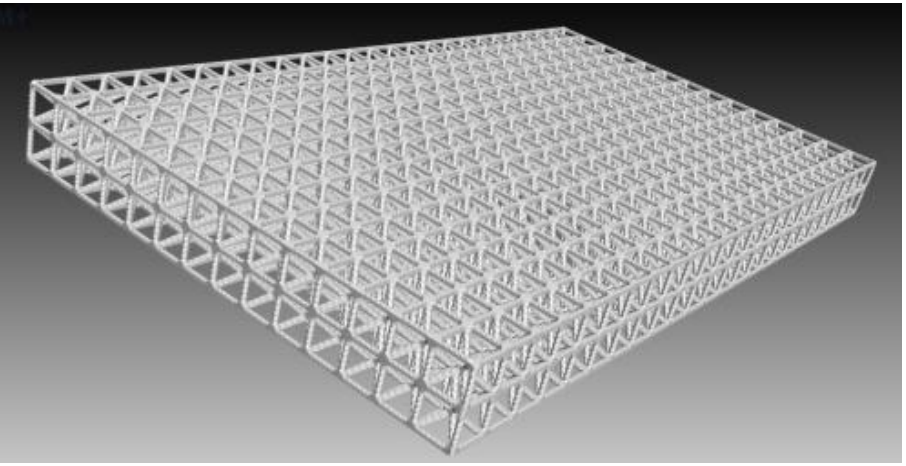
$$-\begin{pmatrix} ||\nabla \boldsymbol{P}|| \\ \boldsymbol{\theta_p} \\ \boldsymbol{\gamma_p} \end{pmatrix} = \mu \overline{\overline{K^{-1}}} \begin{pmatrix} ||\mathbf{U}|| \\ \boldsymbol{\theta_u} \\ \boldsymbol{\gamma_u} \end{pmatrix} + \rho \bar{\bar{\beta}} ||\boldsymbol{U}|| \begin{pmatrix} ||\mathbf{U}|| \\ \boldsymbol{\theta_u} \\ \boldsymbol{\gamma_u} \end{pmatrix}$$

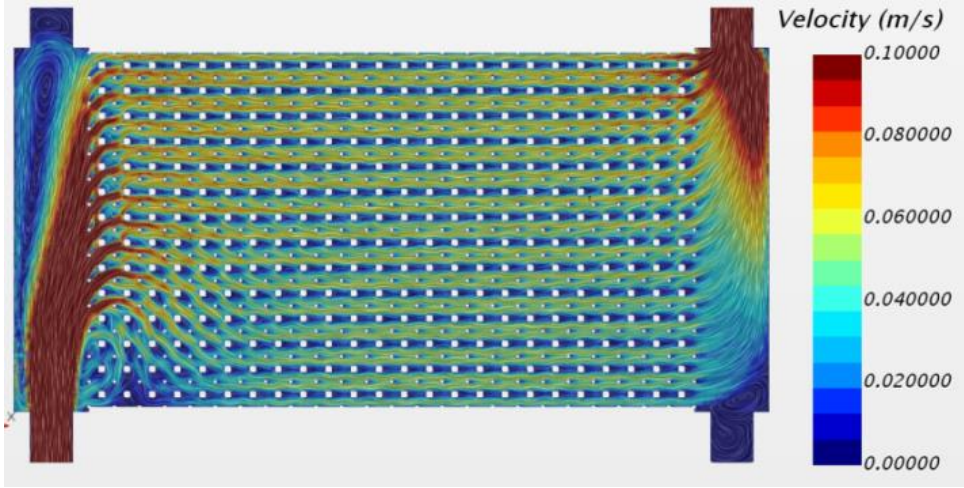
Example : cold plate sizing

Cold plate 0D – sizing



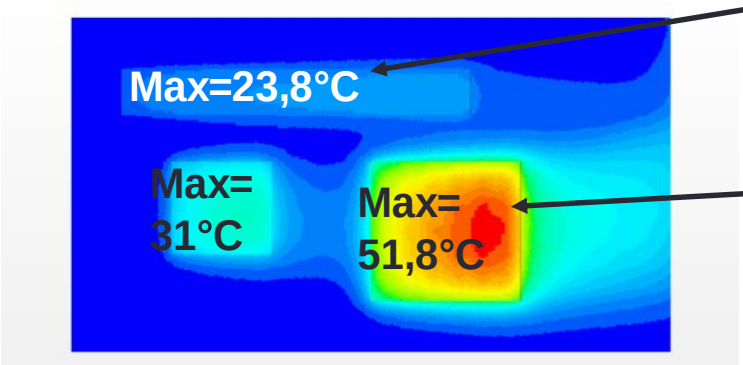
- Objectives :
  - Junction temperature limitations
  - Pressure drop limitation
  - Weightless
- Methodology
  - Using lattice heat transfer and fluid flow correlation
  - Give a uniform pattern for the lattice





CFD results analysis

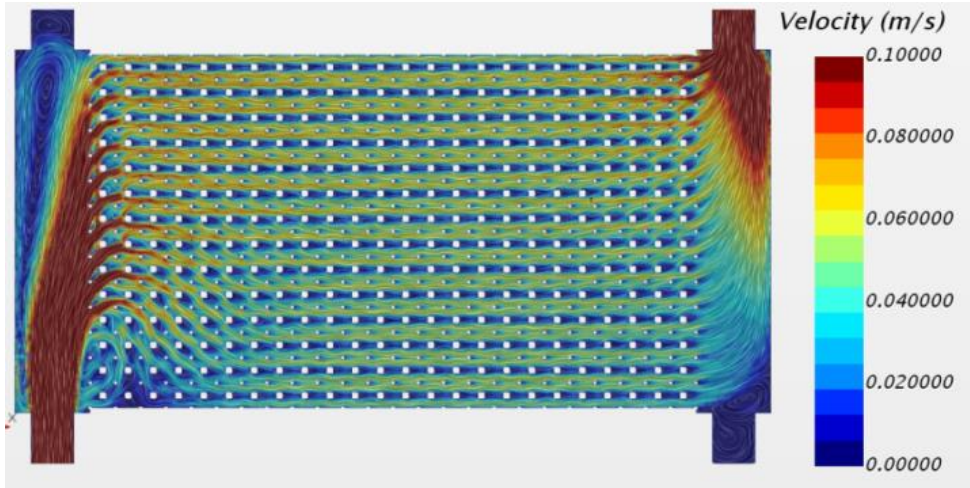
Non uniform temperature field



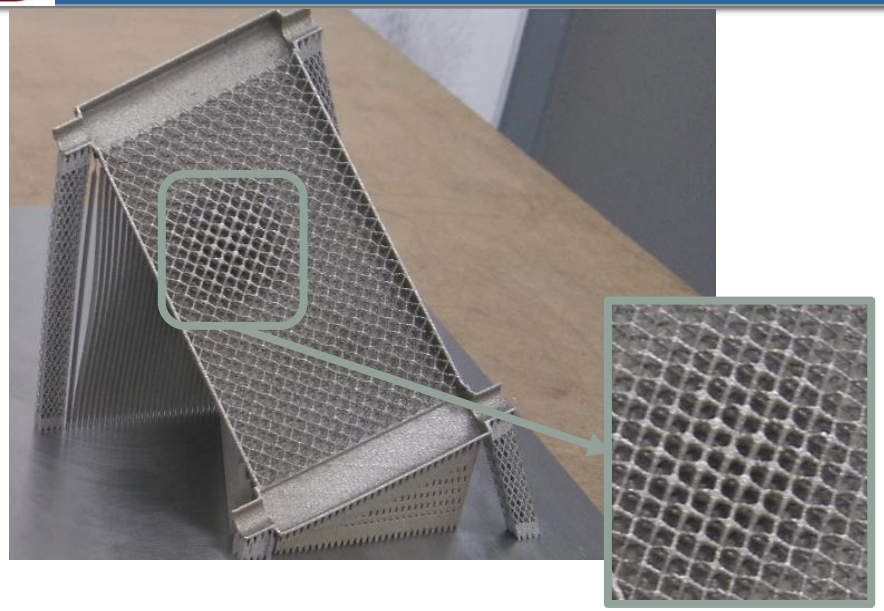
Far from temperature limit

Close to temperature limit

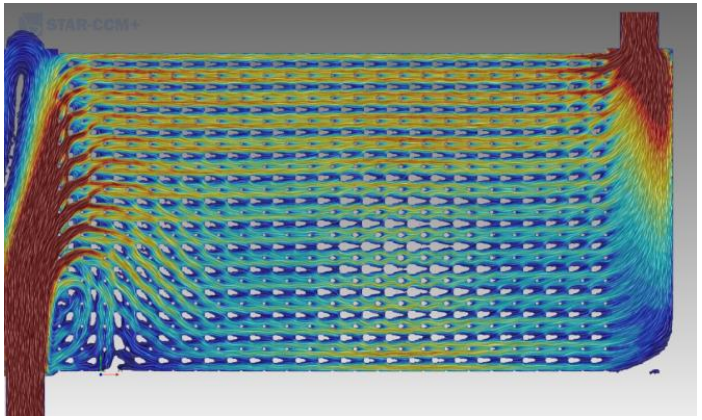
Uniform fluid flow

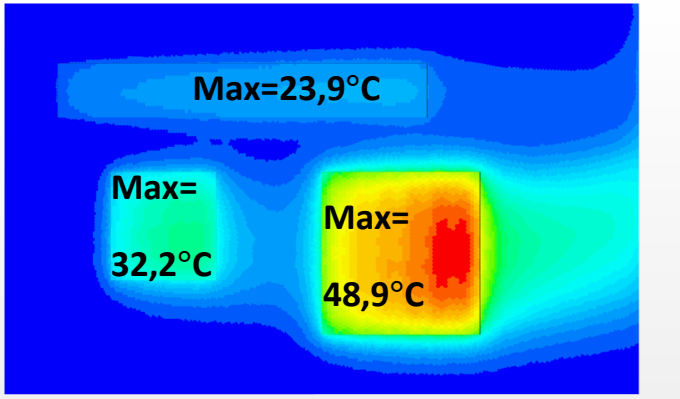


Porous approach



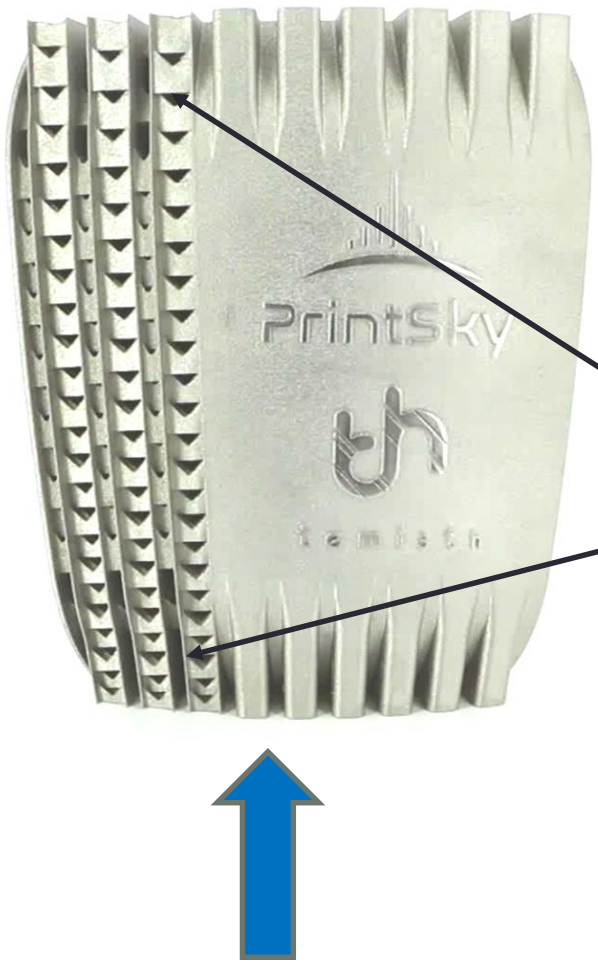
- Modify local structure
- Add thermal conductivity in hot flux area
  - Without avoiding fluid flow
- Remove metal where there is no heat flux
  - Maintain mechanical properties





- -10% of mass
- -7% of pressure drop

Other example



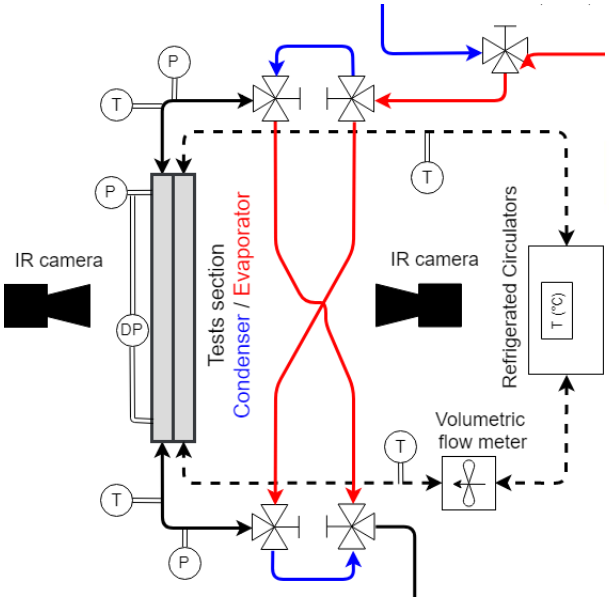
- Cold air inlet
- Sharp increase in temperature

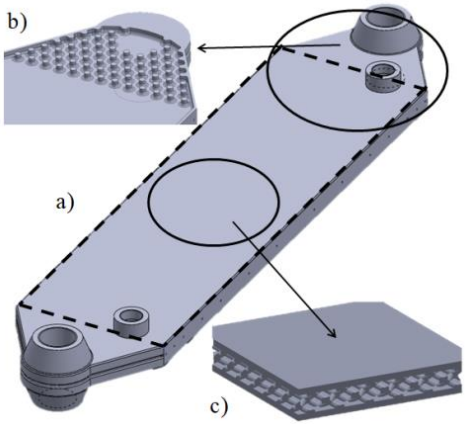
➔Decrease in density
➔Increase of velocity
➔Increase of pressure drop

- Evolutive channel
  - Velocity and pressure drop reduction
- Evolutive fins
  - Maintain fin efficiency

Extension to two phase flow

iusti UMR 7343





14 T-type thermocouples inside the separating wall

Refrigerant channel side

Water channel side

(T) Type T thermocouples

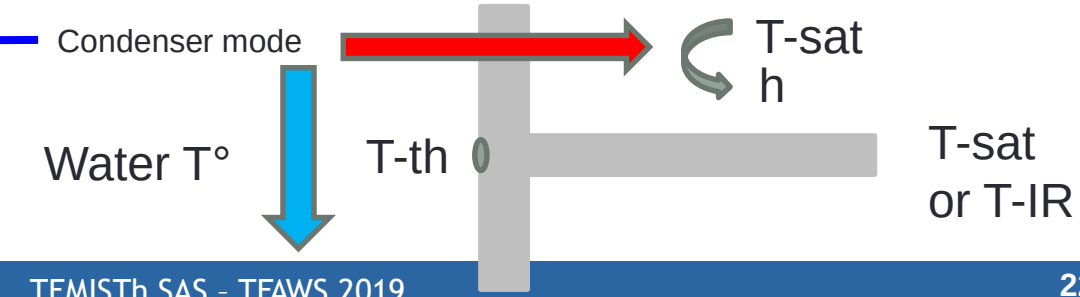
(P) Absolute pressure sensor

(DP) Differential pressure sensor

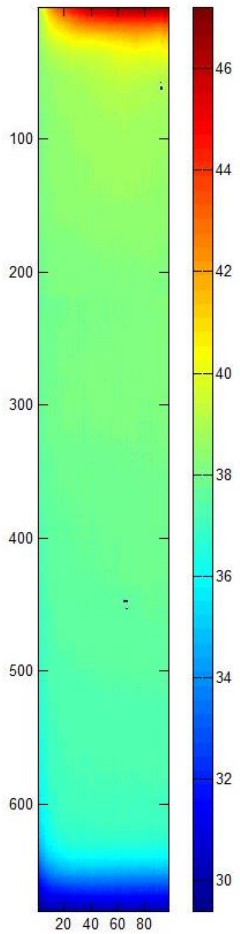
Hydraulic circuits:

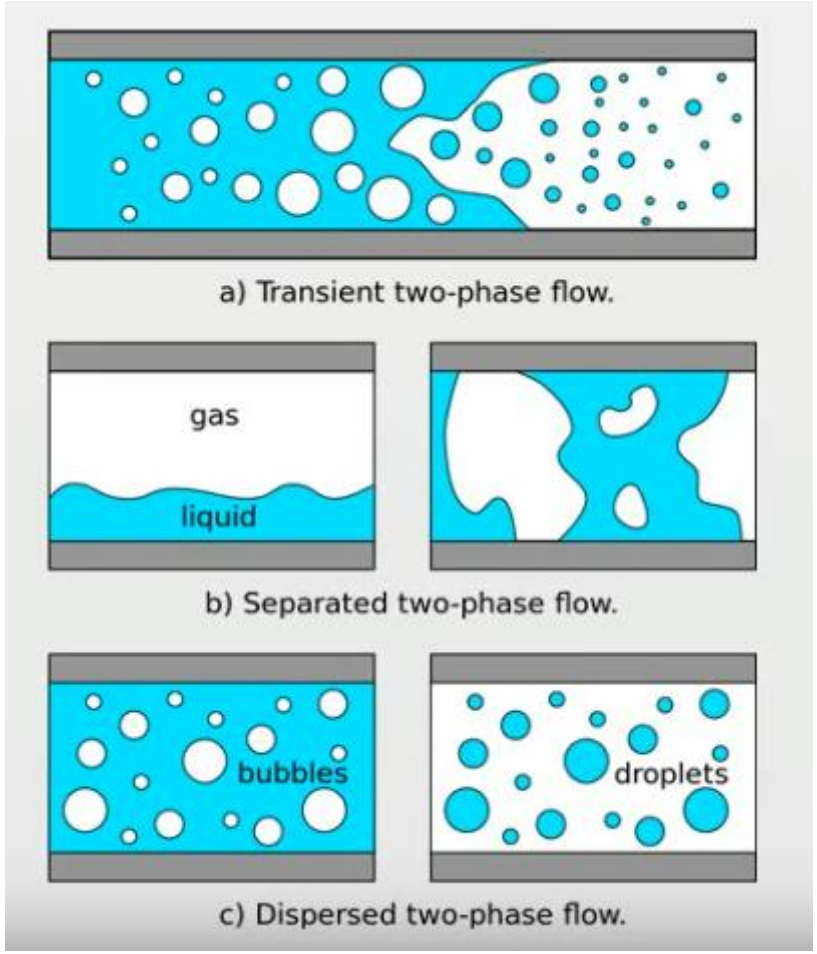
Evaporator mode

Condenser mode



Condenser optimization





- Fins
- Lattice structure
- Pin arrays

- Porosity depends on liquid mass fraction

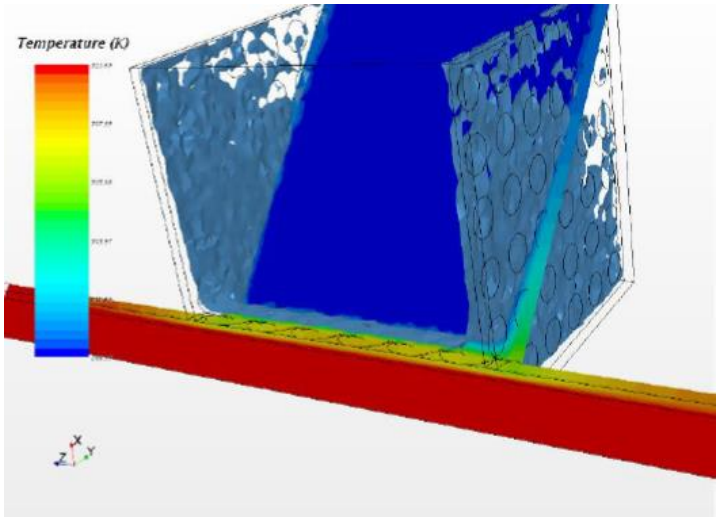
Phase material + lattice

- Is porous approach available for PCM ?

$$\varepsilon(\rho C_P)_f \frac{\partial T_f}{\partial t} + \varepsilon(\rho C_P)_f \cancel{U.\nabla \boldsymbol{T}_f} = \nabla.\left(\lambda_f^{eff} \nabla \boldsymbol{T_f}\right) + hS_p(T_f - T_S)$$

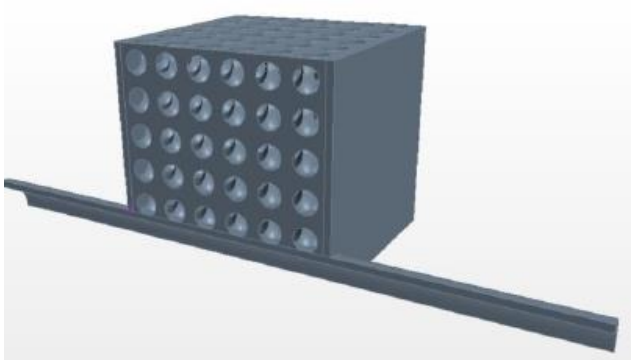
$$(1-\varepsilon)(\rho C_P)_S \frac{\partial T_S}{\partial t} = \nabla.\left(\lambda_S^{eff} \nabla \boldsymbol{T_S}\right) + hS_p(T_S - T_f)$$

- No fluid flow
- How to estimate heat transfer coefficient ?



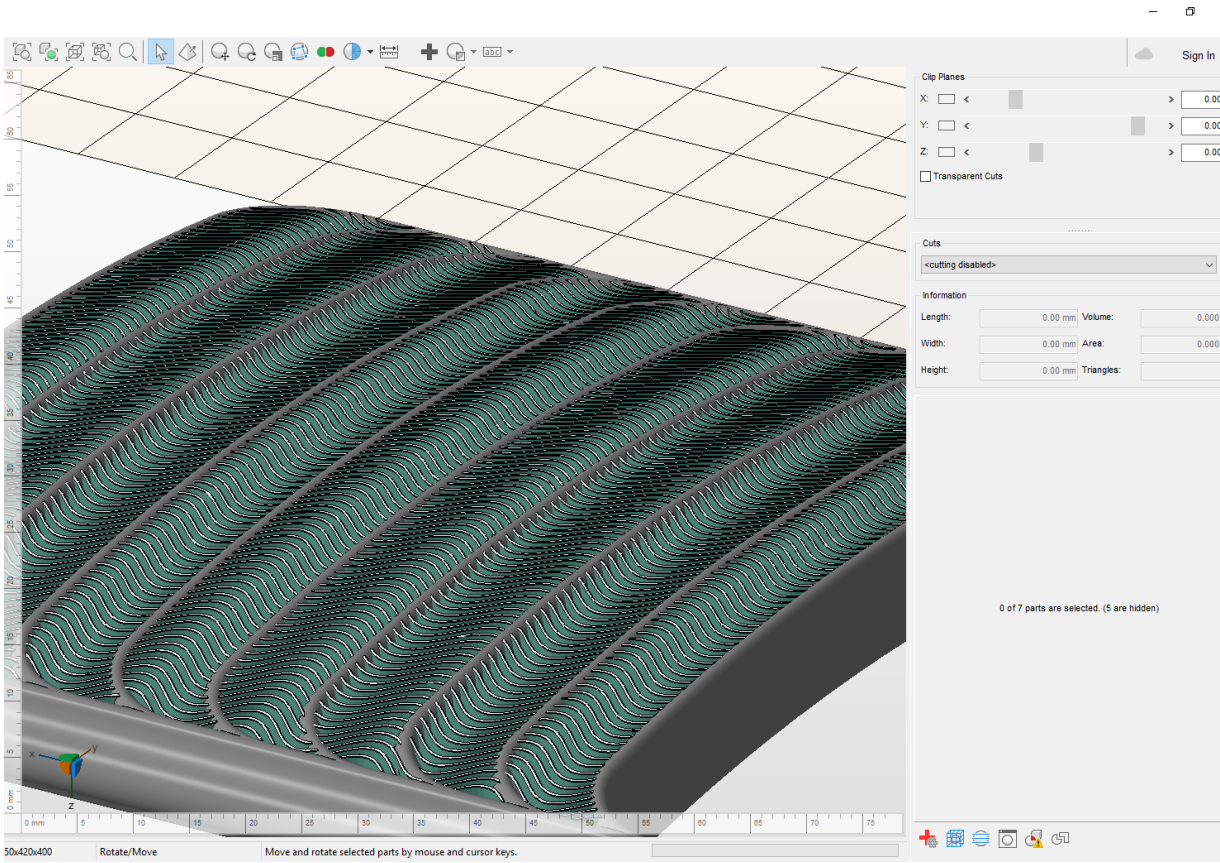
➔Using a step by step value approach

➔The coefficient is available for one boundary conditions



Porous approach applied for CAD generation

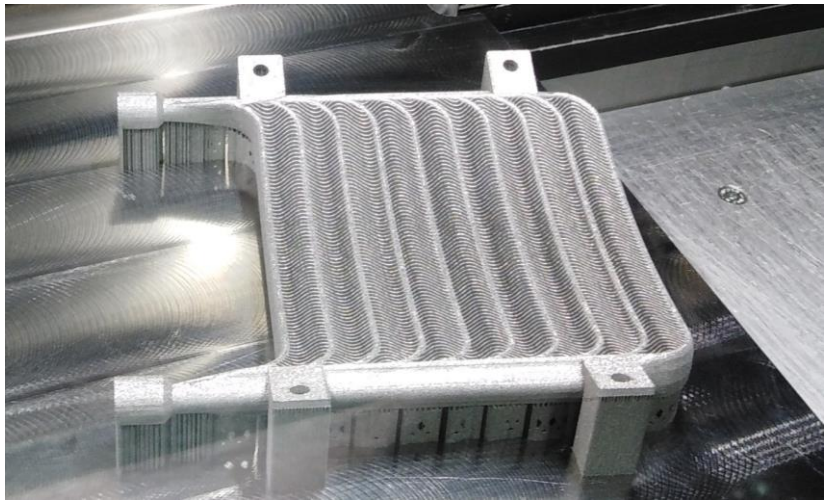
- Tubes and fins are generated separately
- 1 stl file for fins
- 1 stl file for tubes
- 1 Laser strategy per file



Conclusions

- An equivalent porous approach is developed for cellular materials
  - In single phase flow
  - A two phases flow model is in progress
  - PCM model is not working

- This approach can be easily used for additive manufacturing
  - CAD can be considered as a porous media
  - Files for 3D printer can be separated for classical parts and porous parts



Thank you for your attention !

jean-michel.hugo@temisth.com
contact@temisth.com
+33 6 78 84 97 98
Bâtiment TEAM Henri-Fabre
Zone des Florides – 13700 MARIGNANE
FRANCE