Topology Optimization of High-Temperature Volumetric Solar Absorbers Using a Homogenized Porous Media Approach

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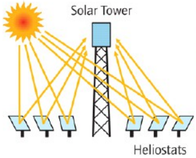
InterPores 19-22 May 2026

Context

System-level objective: decarbonization of high-temperature industrial processes (T > 1000 °C)
⇒ Need for efficient and sustainable energy conversion systems
⇒ Development of high–temperature concentrated solar absorbers (air production up to 1000 °C)



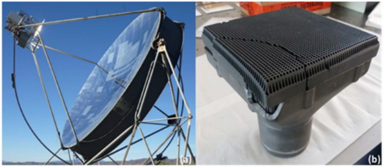


Fig. 6. SiC volumetric absorber test bench in operation at DISTAL Dish-II concentrator on the Plataforma Solar de Almería (a) and cracked volumetric absorber cup (b).

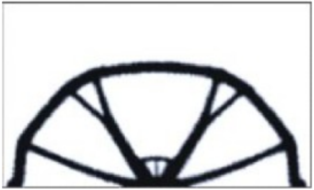
Challenge : Prevent absorber cracking and minimize radiative losses → ANR ORCHESTRA

Topology optimization

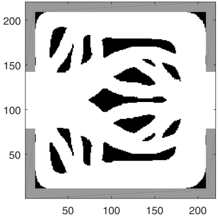
The objective is to minimize a cost function that depends on the state of a system :

$$\min_{\alpha} \ \mathcal{J}(\alpha, \phi(\alpha)) \quad \text{subject to} \quad F(\alpha, \phi) = 0,$$

Where $\mathcal{J}$ is the cost function of the optimization problem, α is the design parameter, ϕ represents the state variables associated with a physical problem, and $F(\alpha, \phi)$ denotes the equations of the physical problem (expressed as equality constraints).



Optimized solid distribution of a brigde by Agyekum [7]

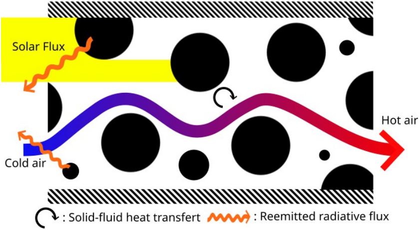


Optimized fluid/solid distribution of fluid flow with thermal therms by Dugast *et al.* [8]

[7] Agyekum, Cangemi *et al.* Optimization and engineering, 2024
[8] Dugast, Favennec *et al.* *Journal of Computational Physics*, 2018.

Homogenized model

- Gaussian or uniform radiative
- flux ≈ 1 MW/m²
- Incoming fluid (air) at ≈ 1 m/s
- Inlet temperature: 300 K
- Absorber size: 5 cm



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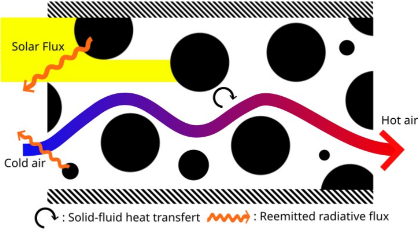
$$\begin{cases} S \cdot \nabla I_s + \beta(\theta) I_s = 0 \end{cases}$$



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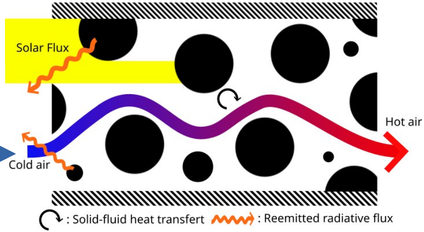

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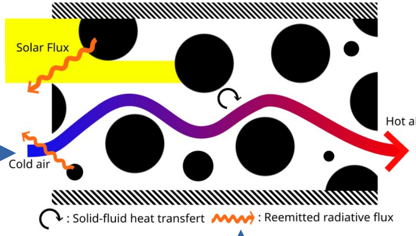

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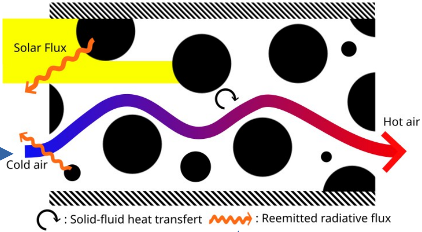

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p : pressure
$\mathbf{u}$: Darcy velocity
β : extinction coefficient
ρ : density
μ : viscosity

K_1 : viscous permeability

K_2 : inertial permeability

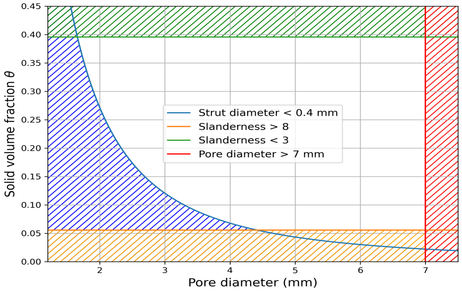
h_ν : convective heat transfer coefficient

Definition of the Design Parameter Space

-Minimum printable strut diameter achievable by the printer : $d_s \geq d_{s,\min}$

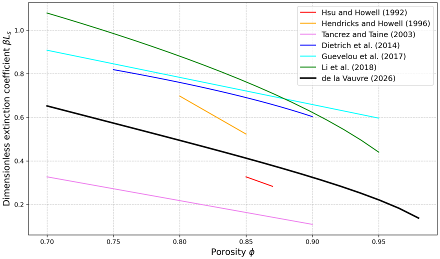
-Strut slenderness constraint : $S_{\min} \leq \dfrac{L_s}{d_s} \leq S_{\max}.$

-Representative elementary volume constraint : $d_p \leq d_{p,\max}$

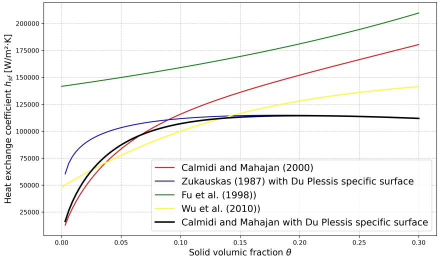


Admissible Design Space Defined by Solid Volume Fraction and Pore Diameter

Comparison of Homogenized Thermophysical Correlations



Dimensionless extinction coefficient as a function of porosity, compared with different correlations from the literature.



Heat transfert coefficient as a function of porosity, compared with different correlations from the literature.

Substantial differences are observed between correlations

Permeability and conductivity correlations:

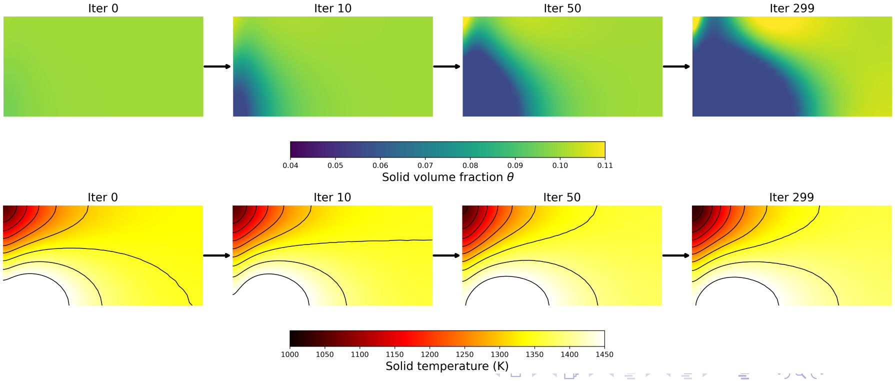
$$K_1 = \frac{d_p^2}{1039 - 1002(1-\theta)} \; ; K_2 = \frac{d_p}{0.5138(1-\theta)^{-5.739}}, \qquad k_{se} = \frac{1}{3}\theta k_s.$$

selected correlations :

$$h_{vol} = S_{spe}\frac{k_f Nu}{d_f} = S_{spe} 0.52 \frac{k_f}{d_f} Re^{0.5} Pr^{0.37}$$

$$\beta = \frac{-1.054 \ln(1 - \theta^{0.46})}{L_s}.$$

Efficiency improved from 83.9% to 85.6%

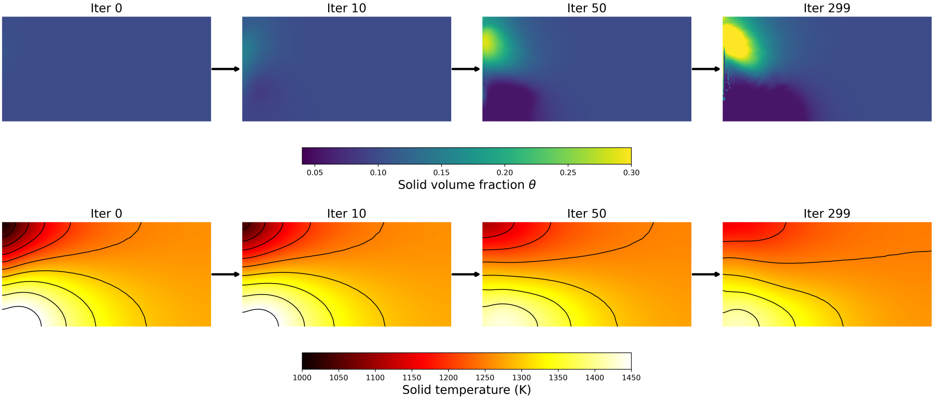


Test case 2 : Efficiency optimization with solid temperature gradient constraint

Addition of an inequality constraint :

$$|\nabla T_s| \leq |\nabla T_s|_{\max}.$$

Maximum thermal gradient reduced from 280 to 120 K·cm^{-1}



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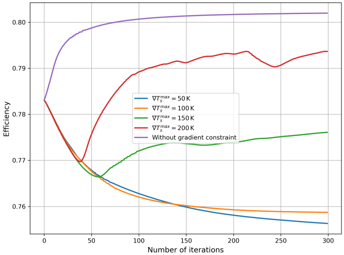
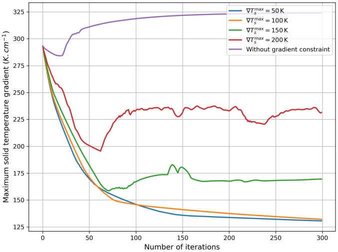


Efficiency evolution during the optimization process for different solid temperature gradient constraint



Maximal solid temperature gradient in the absorber during the optimization porcess for different solid temperature gradient constraint

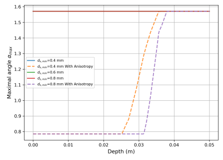
Isotropic optimization good for gradient minimization but not for efficiency

Test case 3 : Efficiency optimization with anisotropy on OPTISOL bench setting

New design parameter :

$$\alpha_{max}$$

Largest allowable angle between struts and the x-axis



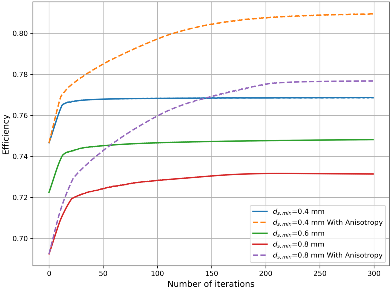
Largest angle at the center

Inlet conditions :

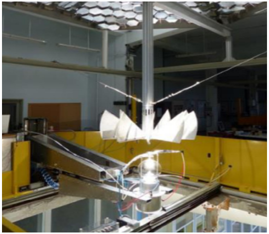
$$I(x=0) = 800\ kW.m^{-2}$$

$$q_{air} = 1\ g/s$$

$$\Longrightarrow\ U_x(x=0) = 0.42\ m/s$$



Efficiency evolution during the optimization process for different minimal struts diameters and anisotropy



- Minimal strut diameter is a key parameter
-Anisotropy enables a 3× better optimization

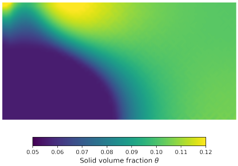
From homogenized optimal fields to discrete porous structures

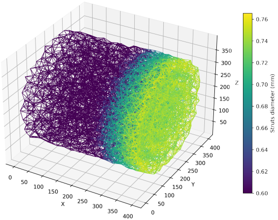
Python code :

Nodes generation
(Random sequential addition)

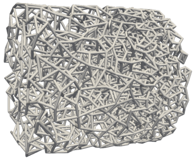
Struts generation

File .stl

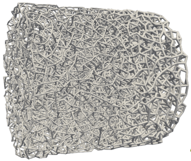




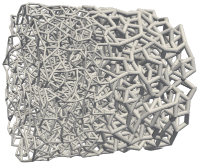
Optimized geometry of the OPTISOL reactor (PROMES) :



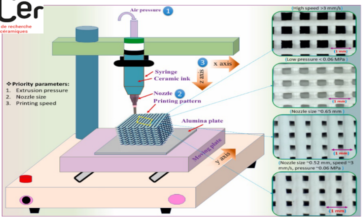
$d_s^{\min} = 0.8$ mm, $q_{\text{air}} = 1$ g/s



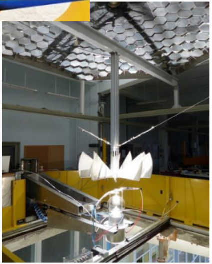
$d_s^{\min} = 0.4$ mm, $q_{\text{air}} = 1$ g/s

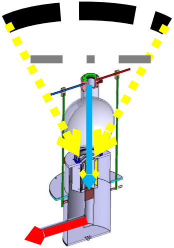


$d_s^{\min} = 0.6$ mm, $q_{\text{air}} = 2$ g/s



Bourret in *Architectured Materials for the Control of Radiative Heat Transfer: Processes for the Development of Architectured Materials with Controlled Radiative and Thermal Properties, Springer, 2026*





Mey-Cloutier et al., Solar Energy 136 (2016) 226–235

Next step : Manufacture the proposed pieces → Experimental test on the Optisol bench at the Promes

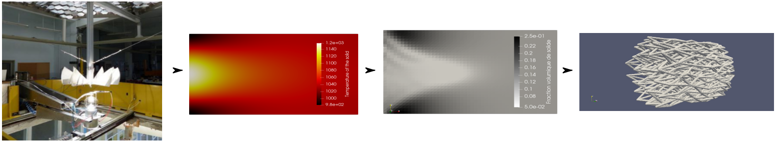
Conclusion

- A complete tool for geometry generation and optimization has been developed

- Efficiency increases with higher porosity at the front surface

- Anisotropy significantly enhances efficiency

- The temperature gradient can be reduced by a factor of two



Merci de votre attention !

Questions ?

Vérification et validation du modèle P-1

Le modèle P-1 est définie a la limite diffusive, c'est-à-dire $\omega = \frac{\kappa}{\beta} \approx 0$.
Or, dans du SiC très absorbant, $\omega \approx 1$

Calcul du Flux sortant pour le modèle P-1

Dans un cas 1D d'un milieu semi-infini, avec T_s et β uniforme on a :

$$\begin{cases} -\frac{1}{3\beta}\frac{\partial^2 G(x)}{\partial x^2} + \kappa(G(x) - 4\sigma_{sb}T_s^4) = 0 \\ -\frac{1}{3\beta}\frac{\partial G}{\partial x}(0) + \frac{G(0)}{2} = 0 \text{ (condition de Marshak)} \\ \frac{\partial G}{\partial x}(+\infty) = 0 \end{cases} \quad (4)$$

On peut donc calculer le flux émit par la surface du milieu :

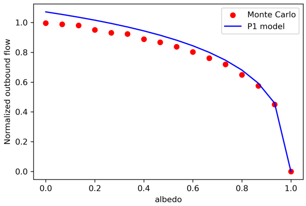
$$q_{P1} = -\frac{1}{3\beta}\frac{\partial G}{\partial x}(0) = \frac{1}{3\beta}\frac{\sqrt{3\kappa\beta}4\sigma_{sb}T_s^4}{2\sqrt{\frac{\omega}{3}}+1} = \frac{4\sigma_{sb}T_s^4}{2+\sqrt{\frac{3}{\omega}}} \quad (5)$$

Pour un scattering nul, c'est-à-dire lorsque l'albédo ω est égal à 1.
On peut calculer analytiquement le flux émis à partir de l'ETR :

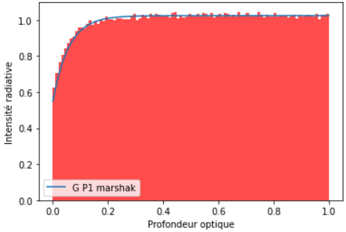
$$q_{exacte} = \iint_{demisphere} \int_0^{+\infty} I_b e^{-\beta x} \omega \cdot n dx d\omega = \sigma_{sb} T^4 \tag{6}$$

$$\frac{q_{P1}}{q_{exacte}} = \frac{4}{2+\sqrt{3}} = 1.072 \tag{7}$$

Le modèle $P1$ donne donc un écart d'environ 7% lorsqu'il n'y a pas de scattering, les autres valeurs de ω ont été comparé à une simulation Monte-Carlo :



Flux sortant en fonction de ω du modèle P-1 comparé à des simulations Monte-Carlo



Champ d'intensité radiatif pour ω = 1

Finite element simulation (FreeFEM)

-Linearization of $\sigma_a T_s^4$ and $\frac{\rho(T_f)}{K_2(\theta)}|\mathbf{u}|\mathbf{u}$:Newton–Raphson method

-SUPG scheme for advection/transport terms

- Computation time < 3 s

Computation of the function gradient:

- 2 design parameters: solid volume fraction θ and pore diameters d_p
- Adjoint-state method (linear system)
- Computation time < 1 s
- ≈ 300 optimization iterations

Total optimization time < 10 minutes