3D Topology Optimization of Heat Sinks for Liquid Cooling

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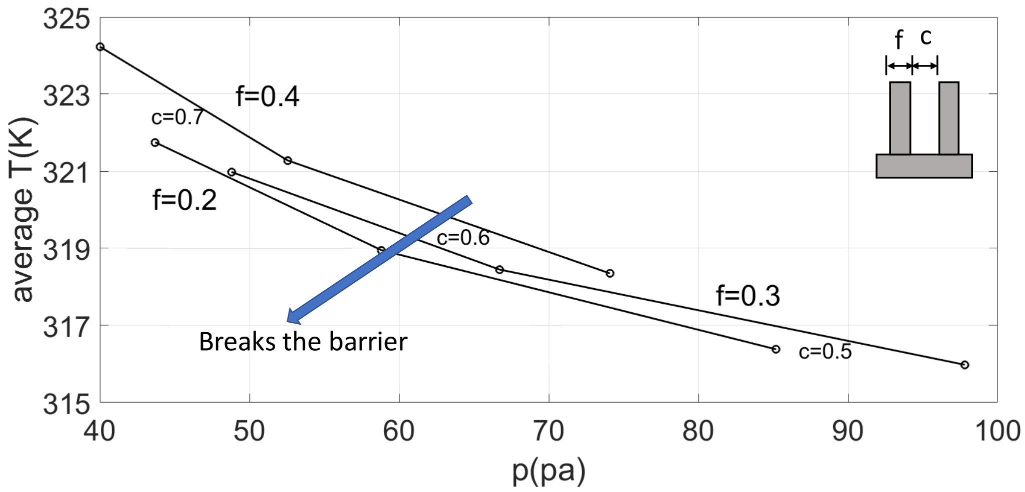
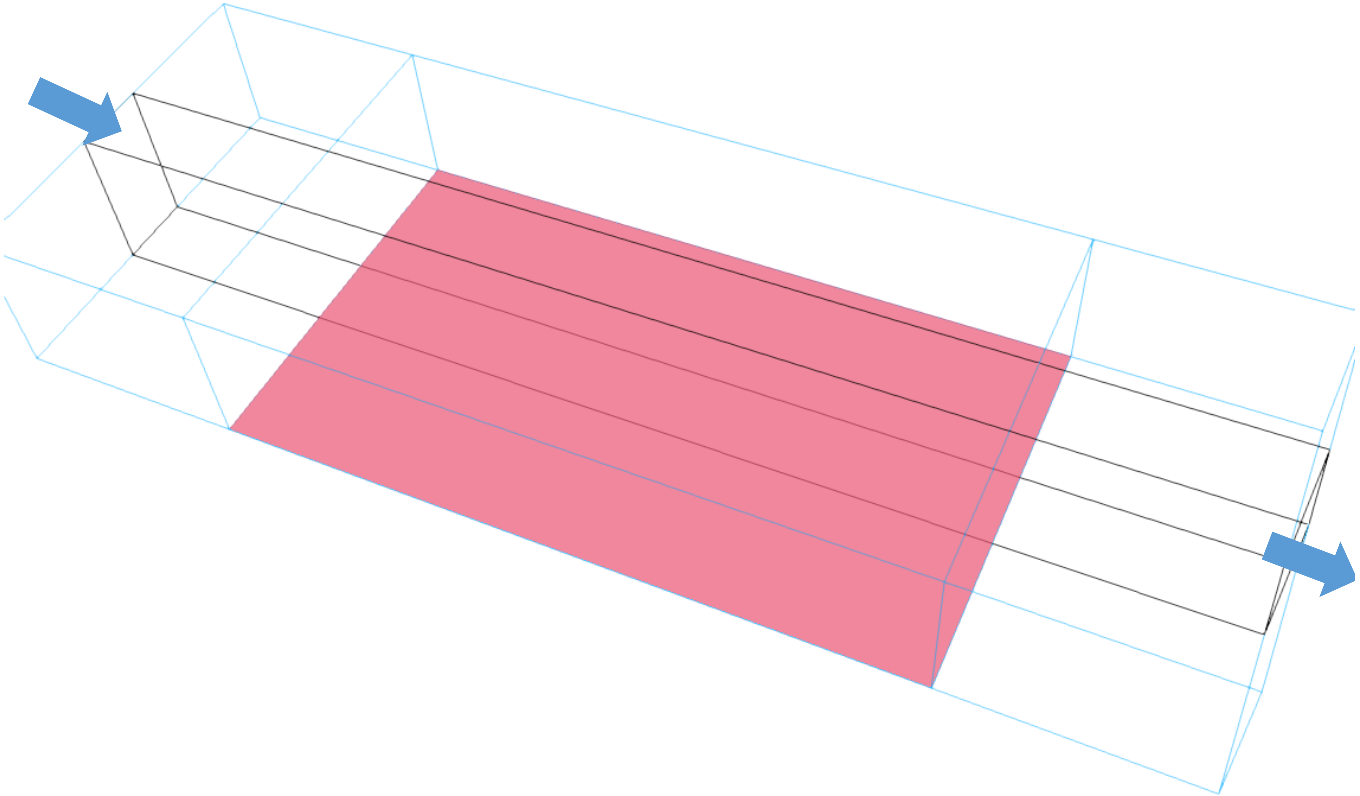
Introduction



- Nowadays the electronics have greater power density and smaller size
- Conventional heat sinks face the restriction of dissipating more heat while consuming less energy
- Topology optimization method combining with additive manufacturing shows the potential to solve the problem

Design problem



- Symmetric boundary on two sides
- Parabolic inlet condition
- Heat flux from bottom

Design problem

$$\min_{\gamma} \quad J = \frac{\int_{\Gamma_{sc}} T d\Gamma_{sc}}{\int_{\Gamma_{sc}} d\Gamma_{sc}} \tag{1a}$$

$$s.t. \quad -\nabla \cdot \nu \nabla \mathbf{u} + (\mathbf{u} \cdot \nabla \mathbf{u}) + \nabla p = -\alpha(\gamma)\mathbf{u} \tag{1b}$$

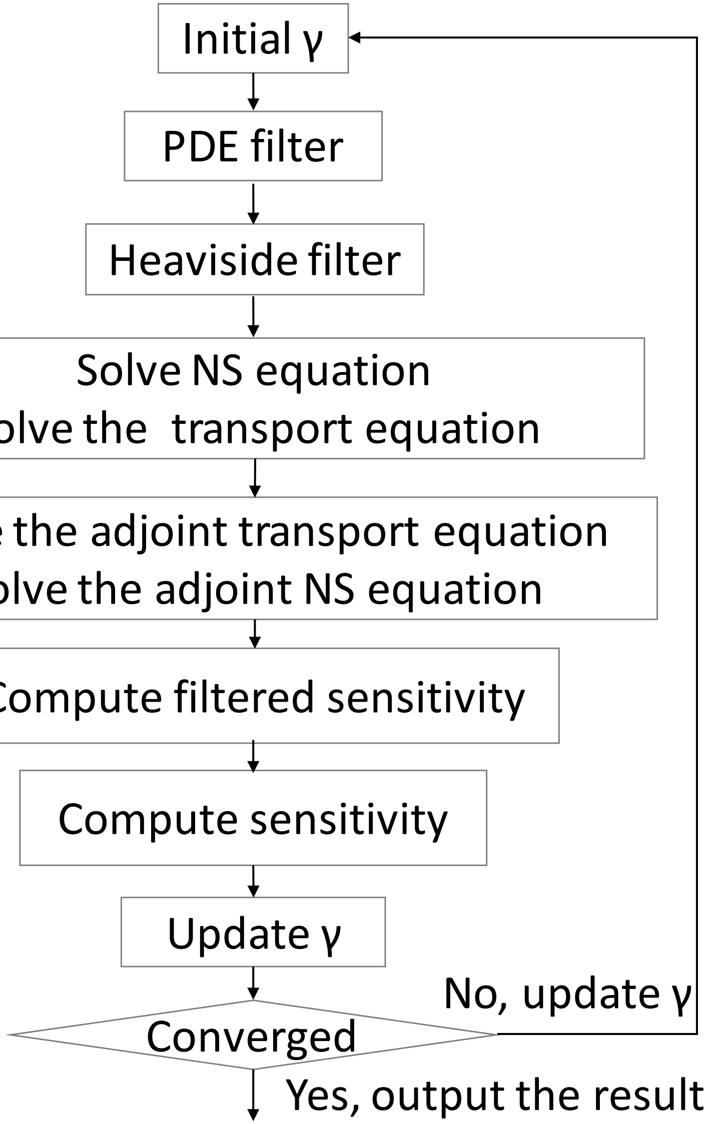
$$-\nabla \cdot \mathbf{u} = 0 \tag{1c}$$

$$\chi(\gamma)\frac{\rho c}{\kappa_f}(\mathbf{u} \cdot \nabla T) = \nabla(\kappa(\gamma) \cdot \nabla T) \tag{1d}$$

$$\int_{\Omega} \frac{1}{2}\mu|\nabla \mathbf{u}|^2 d\Omega + \int_{\Omega_1} \alpha(\gamma)|\mathbf{u}|^2 d\Omega_1 \leq \Phi. \tag{1e}$$

where $\alpha(\gamma) = \alpha_{min} + (\alpha_{max} - \alpha_{min})\dfrac{q(1-\gamma)}{q+\gamma}$, with $\alpha_{min} = 0$ and $\alpha_{max} = \nu/(DaL^2)$

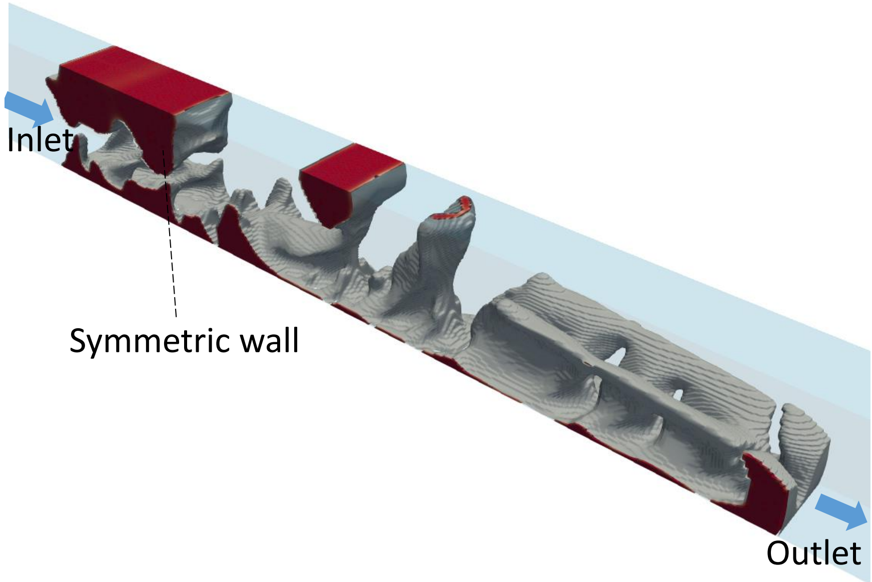
Optimization process

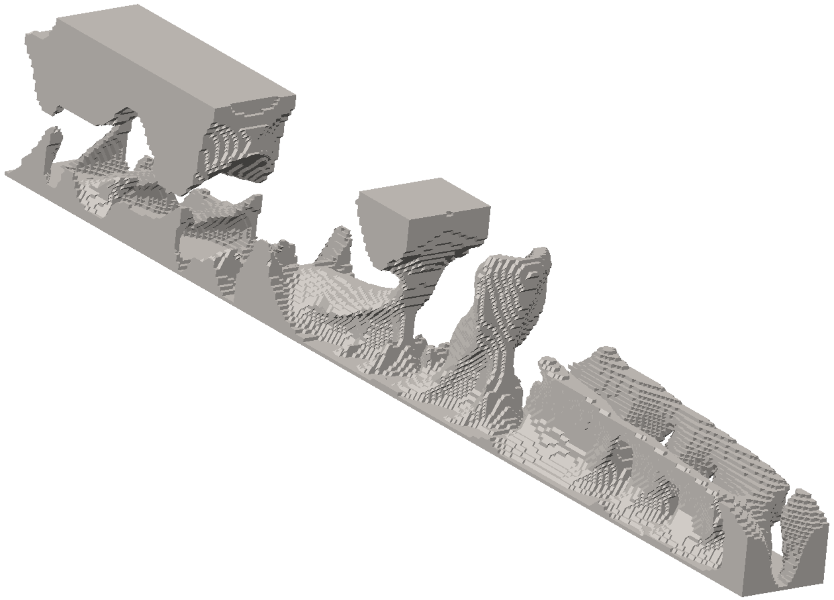


Optimization process

- Navier-Stokes equations are discretized with equal order elements with SUPG/PSPG stabilization
- Continuous consistent adjoint equations are used
- State and adjoint Navier-Stokes equations are solved with PCD(pressure convection-diffusion) preconditioner
- Solvers are implemented with open source finite element software FEniCS
- 96 CPUs, 6.4 million tetrahedron cells
- Approx. speed: 20-60 minutes for each optimization iteration, 2 weeks for the total optimization

TO result

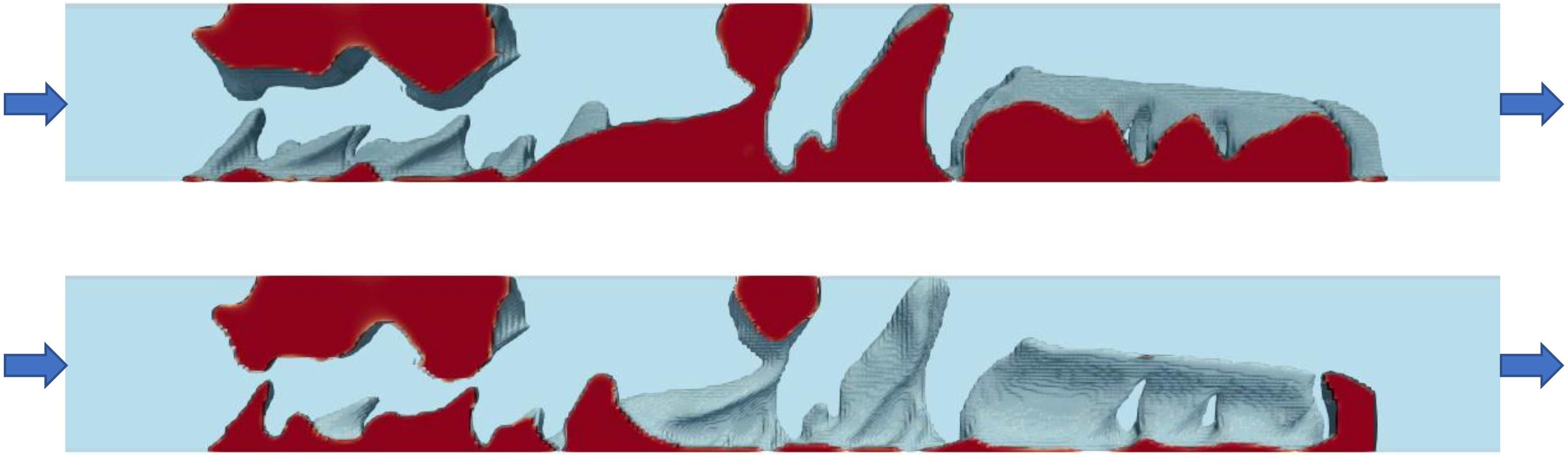




3D TO design and geometric model

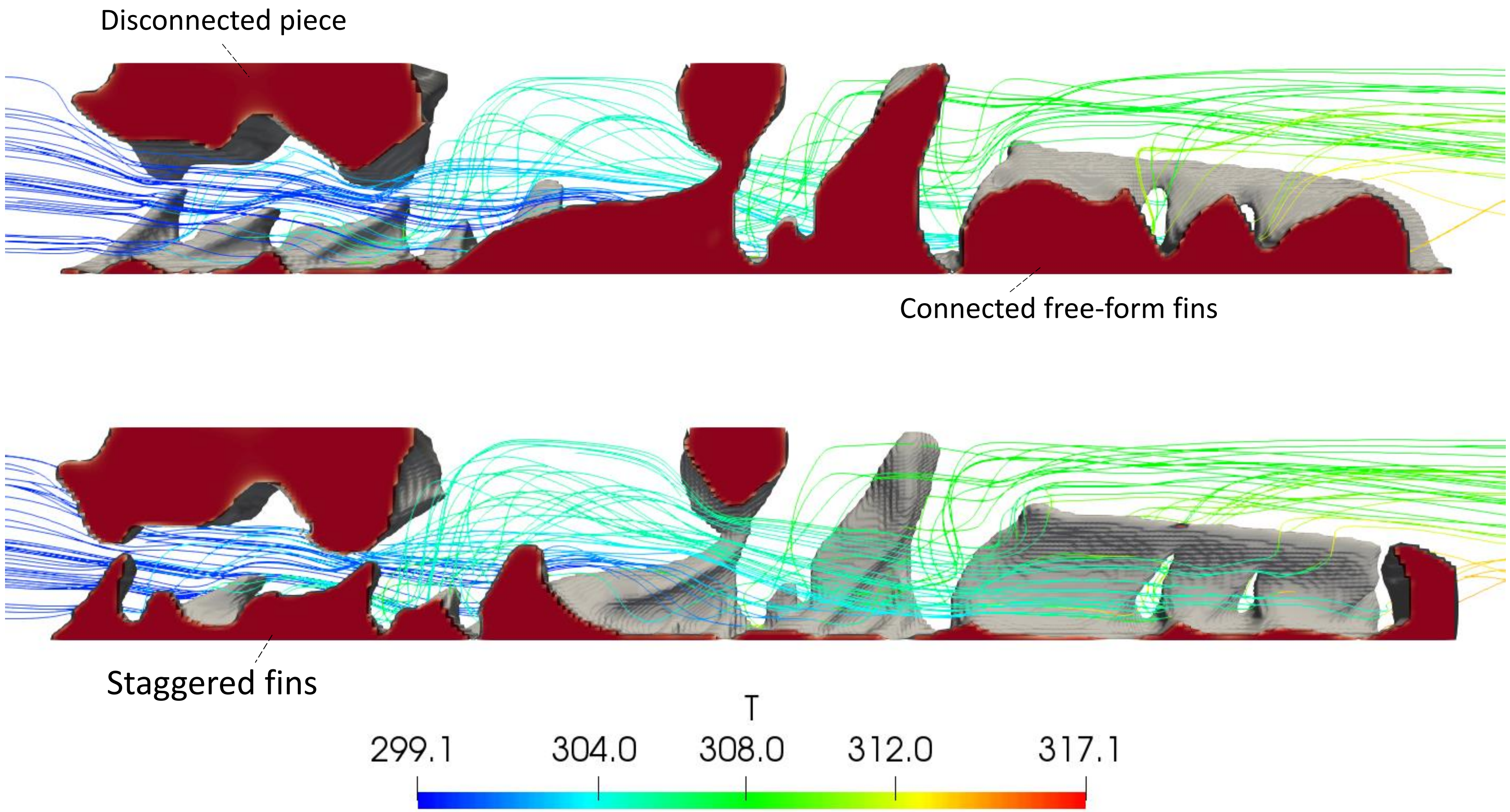
TO result

TO result



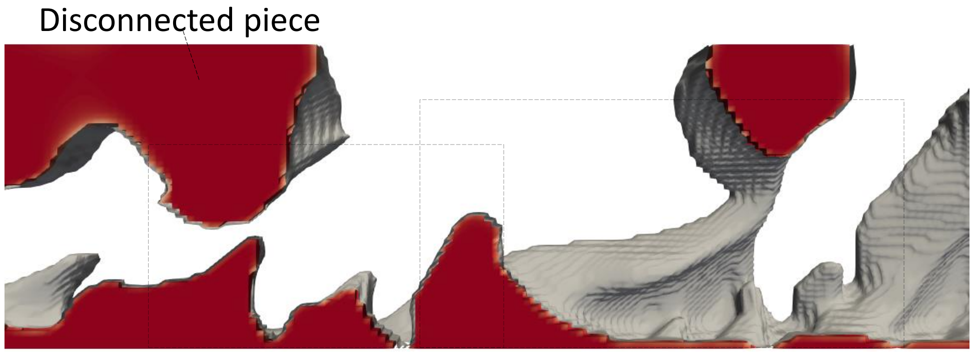
Design viewed from the left side and cut from the middle plane

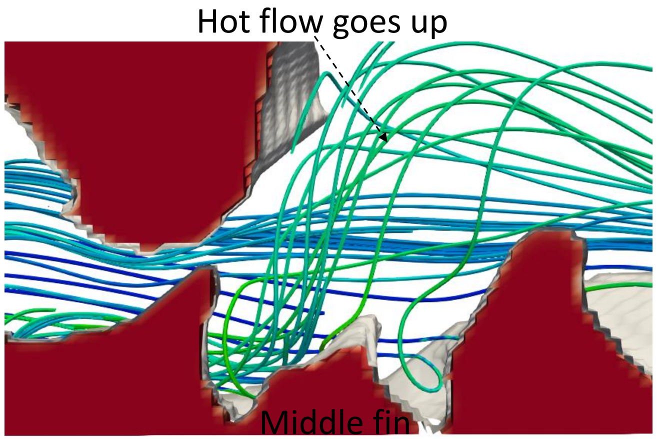
Cooling mechanism: flow split

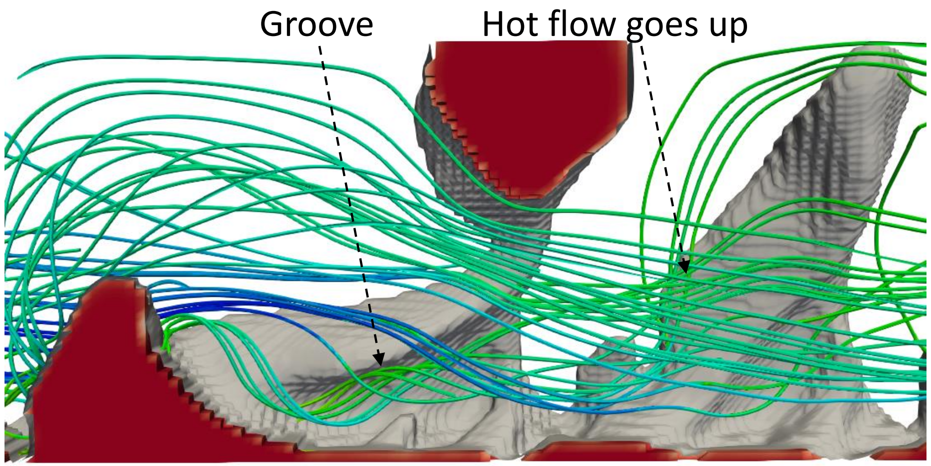


- Hot flow from upstream is sent to top layer
- Cold flow from upstream is sent to bottom layer

Cooling mechanism: flow split

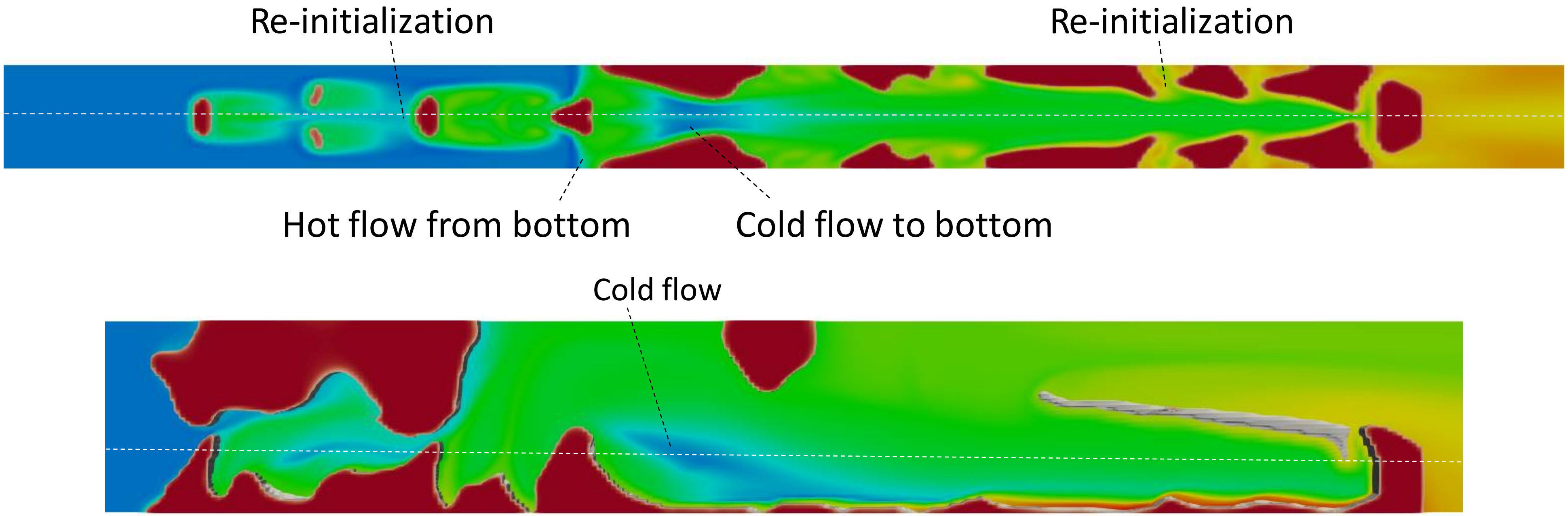






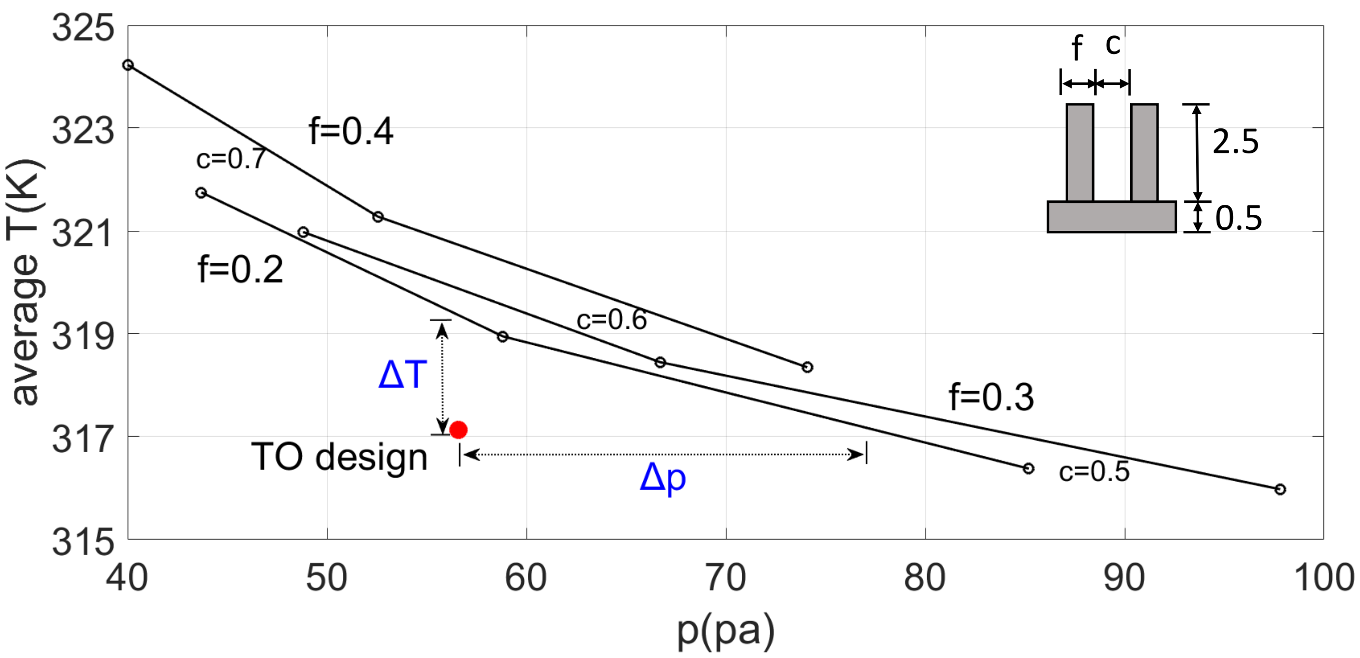
- Hot flow from upstream is sent to top layer
- Cold flow from upstream is sent to bottom layer

Cooling mechanism: re-initialization



- 2D temperature plot shows the re-initialization effect
- Flow split effect is also shown in the 2D figure

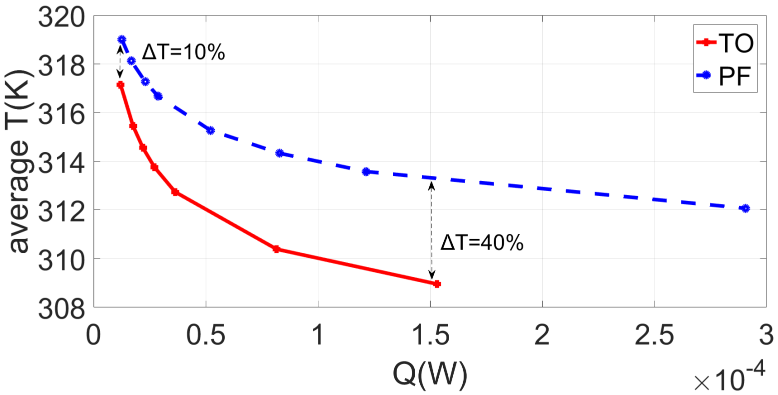
TO design advantages

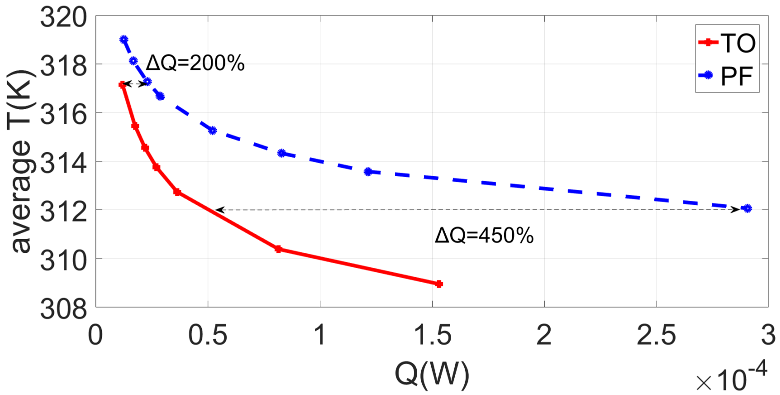


Compared with the TO design, the optimized PF heat sink on the Pareto front

- costs 40% high pressure drop when the temperature is same
- raises the temperature by 10% when the pressure drop is same

TO design advantages

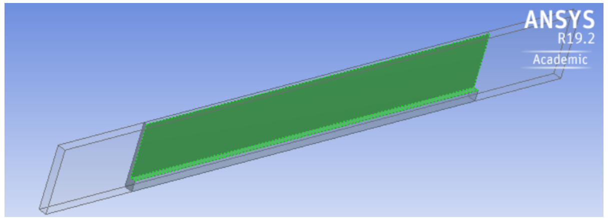


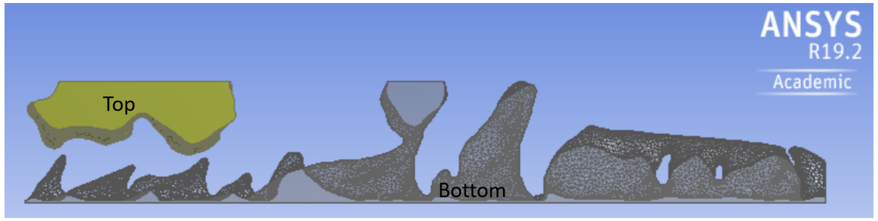


When increasing the flow rate on the inlet

- The temperature of the optimal PF heat sink is 10% to 40% higher than the TO design
- The pumping power of the optimal PF heat sink is 200% to 450% higher than the TO design

Surface area





Surface area measured in Fluent

Surface area: per 0.01m width

- Parallel plate: $1.6 * 10^{-3} m^2$
- TO bottom structure: $0.57 * 10^{-3} m^2$
- TO top structure: $0.08 * 10^{-3} m^2$

TO design show less surface area than the PF heat sink

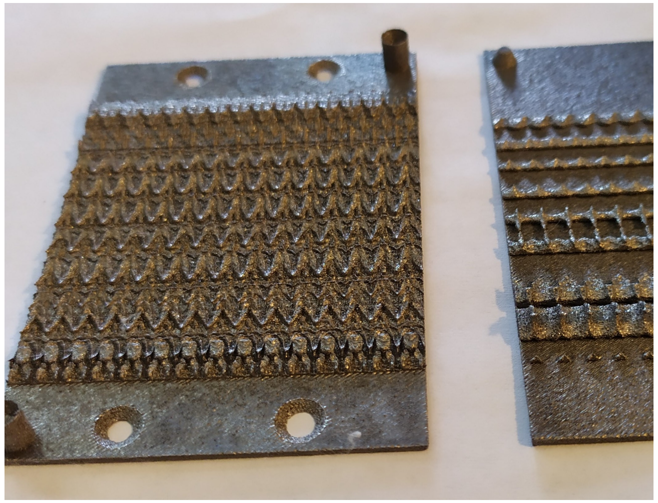
- TO design beat the PF heat sink by better convection
- This is in contrast to optimization without considering the Navier-Stokes equation, which usually gets tree-type structures by increasing the surface area

Conclusion

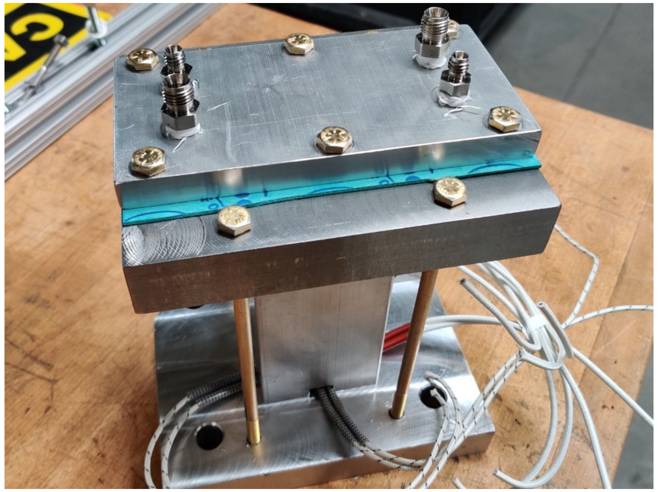
- Topology optimization method is a viable and effective computational design tool for heat sink design
- Compare our topologically optimized design and the optimized conventional plate fin(PF) heat sink:
  - Optimized PF heat sink has 10% higher temperature than TO design when pressure drop is same
  - Optimized PF heat sink cost 40% higher pressure drop than TO design when temperature is same
- Interesting cooling mechanisms automatically emerge from TO and lead to better heat dissipation

Sun, S., Liebersbach, P., & Qian, X. (2020). 3D topology optimization of heat sinks for liquid cooling. Applied Thermal Engineering, 178, 115540.

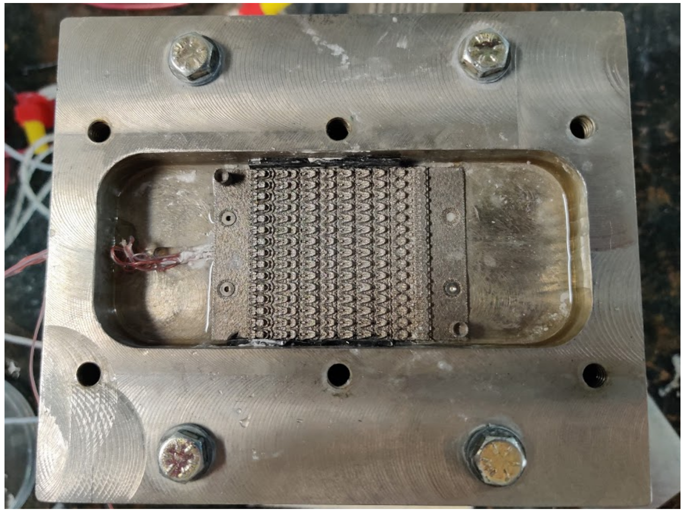
Appendix: heat sink experiments



DLMS printed TO design

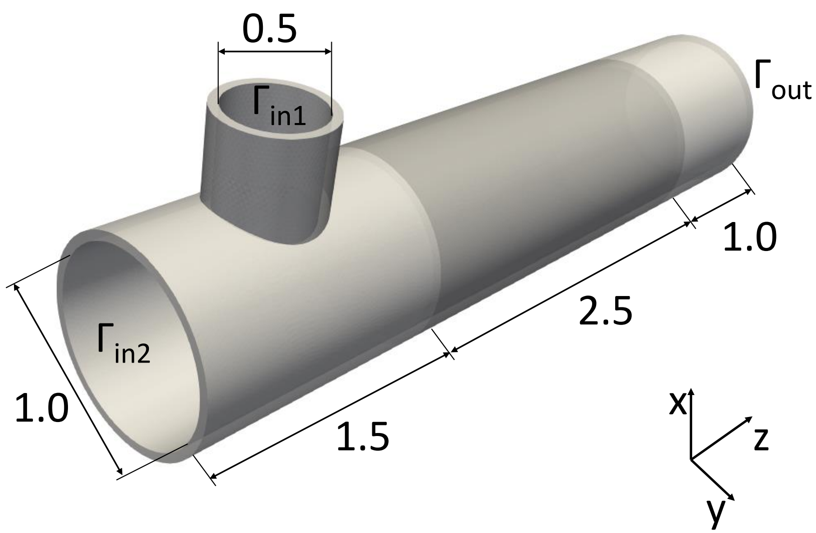


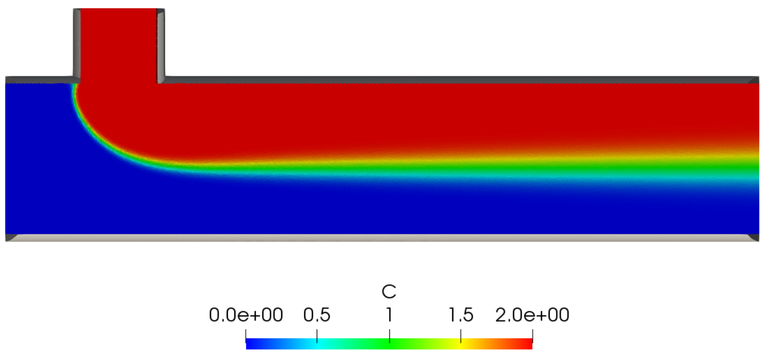
Outside shell



TO design and shell assembled

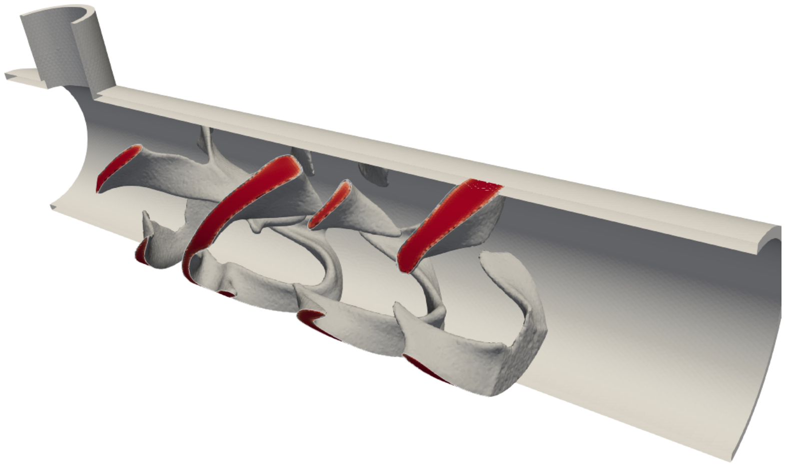
Appendix: static mixers

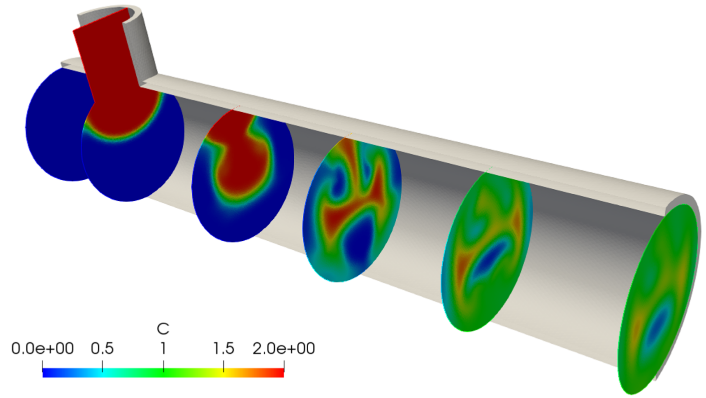


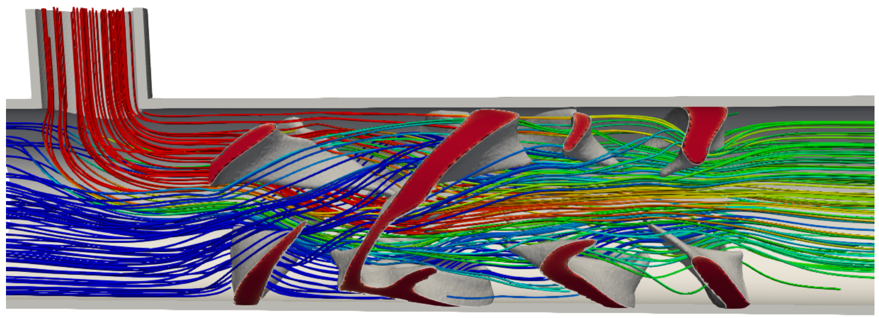


- 10 million tetrahedral cells
- 32 nodes, 2048 CPUs

Appendix: static mixers







- With 2.5 times pressure drop than the open channel, the mixing performance at the outlet is improved by 90%