Topology Optimization of an Actively Cooled Electronics Section for Downhole Tools

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COMSOL
CONFERENCE
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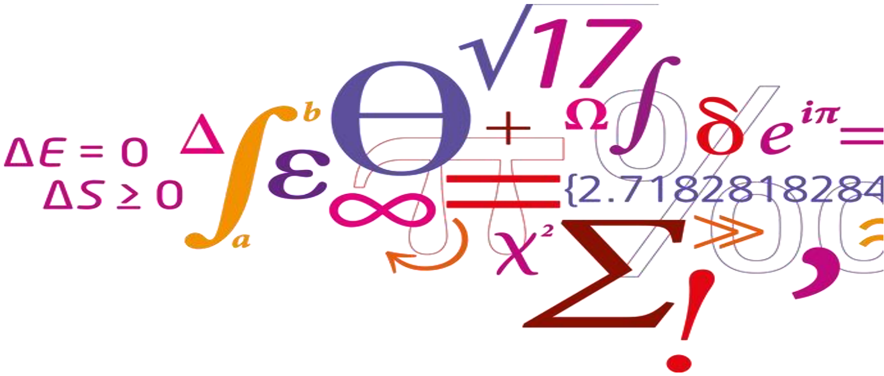

DTU Energy
Department of Energy Conversion and Storage

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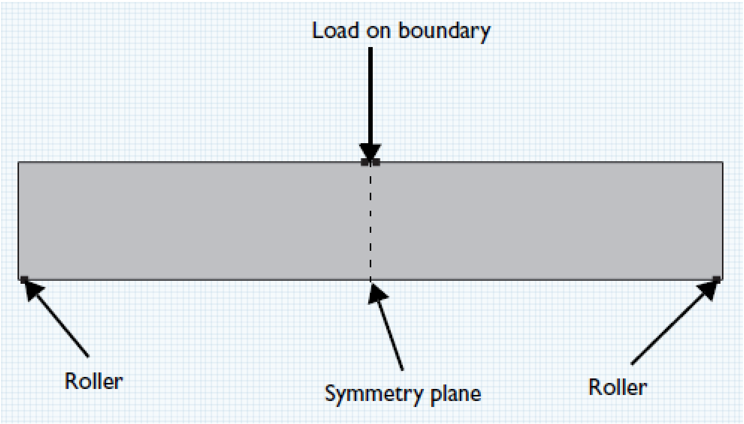
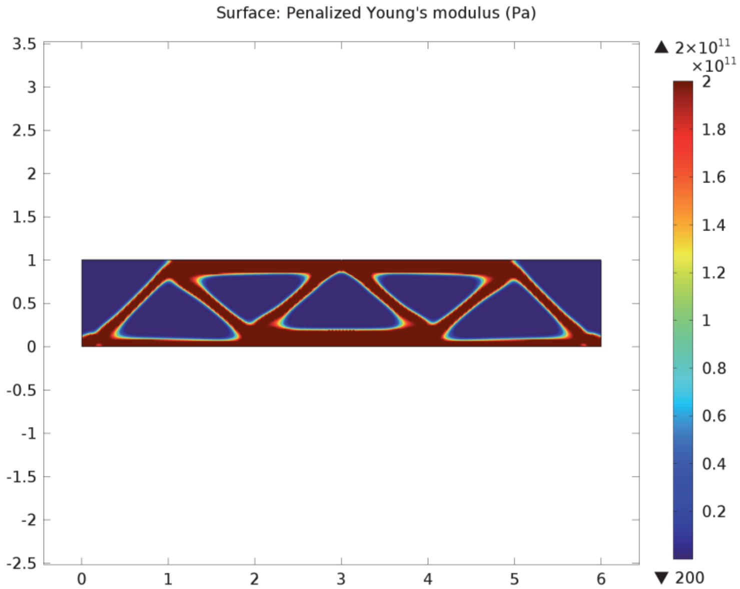
Introduction

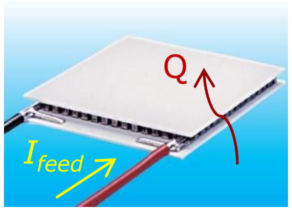
- ***Topology Optimization***: mathematical approach that optimizes the material layout within a given design space and boundary conditions.





Introduction

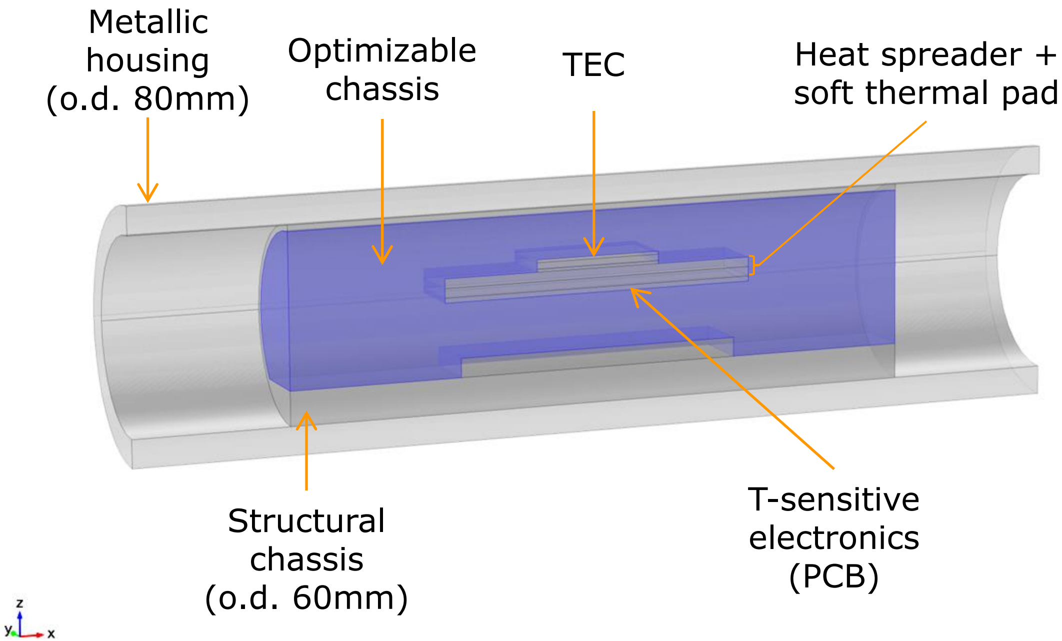
- ***Downhole Tool***: cylindrical robotic tool used to increase or restore the production of oil and gas wells (well cleaning, pipe cutting, installation of valves).



TEC - Thermoelectric (Peltier) cooler:

upgrade the maximum operating temperature from <u>175° C</u> to <u>200° C</u>.

Problem formulation



Design Criteria:

- Use aluminum to enhance the cooler's heat rejection to the well.
- Use thermal insulation to protect the cooled electronics.

Axial section of the downhole tool's implemented geometry.

➔ **Optimize the distribution of aluminum-thermal insulation within the chassis**

➔ **Minimize the average PCB temperature**

Governing equations

- *Heat conduction*

$$\nabla(-k\nabla T) = Q_{source} \qquad (1)$$

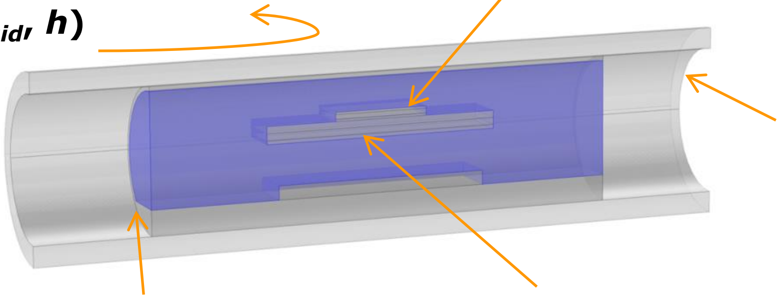

Heat Transfer in Solids *(ht)*

- *Modified heat conduction*

$$\nabla(JST - k\nabla T) = Q_{JouleHeating} \qquad (2)$$


Δu Coefficient Form PDE *(c)*

❖ *Boundary conditions*



Convective heat flux (T_{fluid}, h)

TEC feed current I_{feed}

Thermal insulation

Thermal (contact) resistance

Heat source (1 W)

Topology Optimization Implementation
(SIMP method)

minimize:

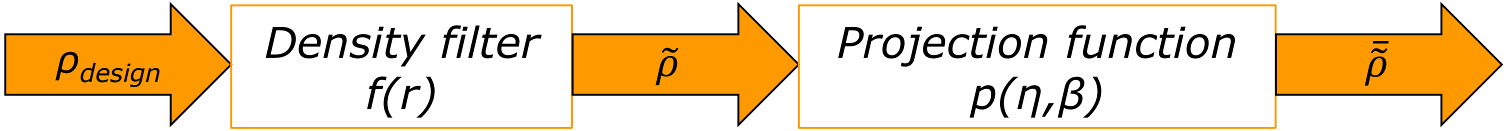
$$f_{obj}\left(T,\rho_{design}\right)=\frac{1}{A_{PCB}}\int_{\Omega_{PCB}} T\,d\Omega_{PCB} \qquad (3)$$


Optimization *(opt)*

constraints:

$$0\le \rho_{design}\le 1 \qquad (4)$$


Optimization *(opt)*


ρ_{design}

Density filter
f(r)

$\tilde{\rho}$

Projection function
p(η,β)

$\bar{\tilde{\rho}}$


Δu Coefficient Form PDE *(c)*


Analytic 1 *(fun)*

interpolation function:

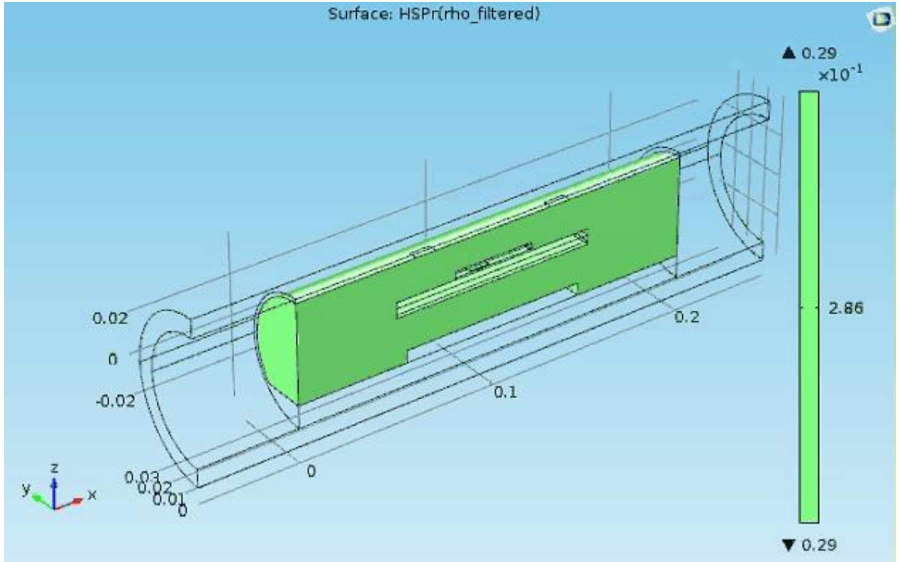
$$k_{SIMP}=k_{ins}+\left(k_{Al}-k_{ins}\right)\bar{\tilde{\rho}}^{p} \qquad (5)$$


a= Variables

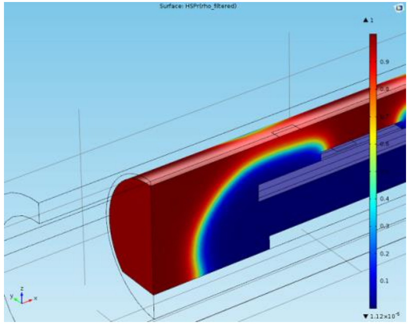
Simulation results

$interpolation\ function:$ $$k_{SIMP} = k_{ins} + (k_{Al} - k_{ins})\bar{\tilde{\rho}}^{p} \quad (5)$$

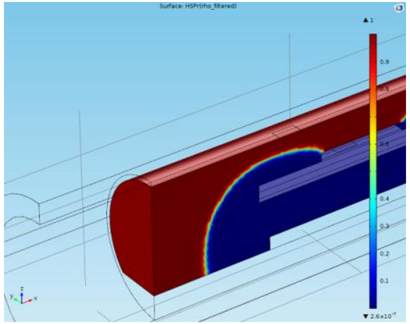
a= Variables



I_{feed} = 4 A h = 50 Wm^{-2}K^{-1}



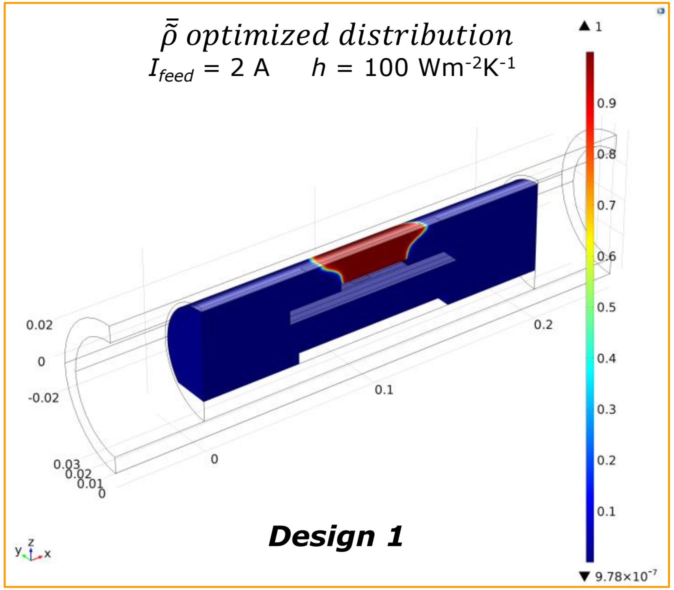
p(η,β = 1)



p(η,β = 8)

Simulation results

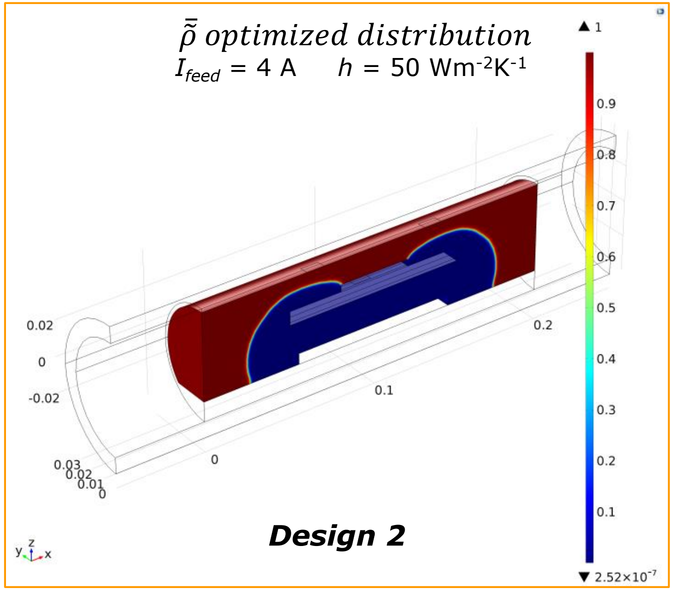
T_{fluid} = 200 ° C h = 25, 50, 100, 500 $Wm^{-2}K^{-1}$ I_{feed} = 1, 2, 3, 4 A



Design 1

Aluminum

Insulator

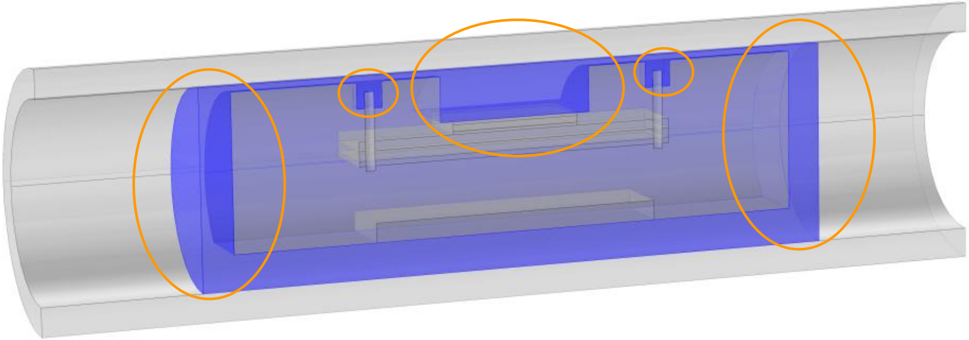


Design 2

- Low I_{feed} / High h
- Aluminum **pad** length grows with I_{feed} and decreases with h.

- High I_{feed} / Low h
- Aluminum **layer** thickness grows with I_{feed} and decreases with h.

Choice of the final design



Axial section of the finally chosen design.

h ($Wm^{-2}K^{-1}$)	Opt - 1A T_{PCB} (° C)	Design - 1A T_{PCB} (° C)	ΔT (K)
25	182.31	181.95	0.10
50	179.32	178.97	0.11
100	177.83	177.47	0.11
500	176.56	176.21	0.11
h ($Wm^{-2}K^{-1}$)	**Opt - 2A T_{PCB} (° C)**	**Design - 2A T_{PCB} (° C)**	**ΔT (K)**
25	175.63	175.68	0.05
50	168.18	168.23	0.05
100	164.54	164.57	0.04
500	161.46	161.48	0.03
h ($Wm^{-2}K^{-1}$)	**Opt - 3A T_{PCB} (° C)**	**Design - 3A T_{PCB} (° C)**	**ΔT (K)**
25	188.22	188.93	0.71
50	171.48	171.87	0.39
100	163.68	163.90	0.22
500	157.12	157.35	0.23
h ($Wm^{-2}K^{-1}$)	**Opt - 4A T_{PCB} (° C)**	**Design - 4A T_{PCB} (° C)**	**ΔT (K)**
25	228.62	233.59	4.97
50	192.79	195.71	2.92
100	177.25	179.29	2.04
500	165.23	166.37	1.14

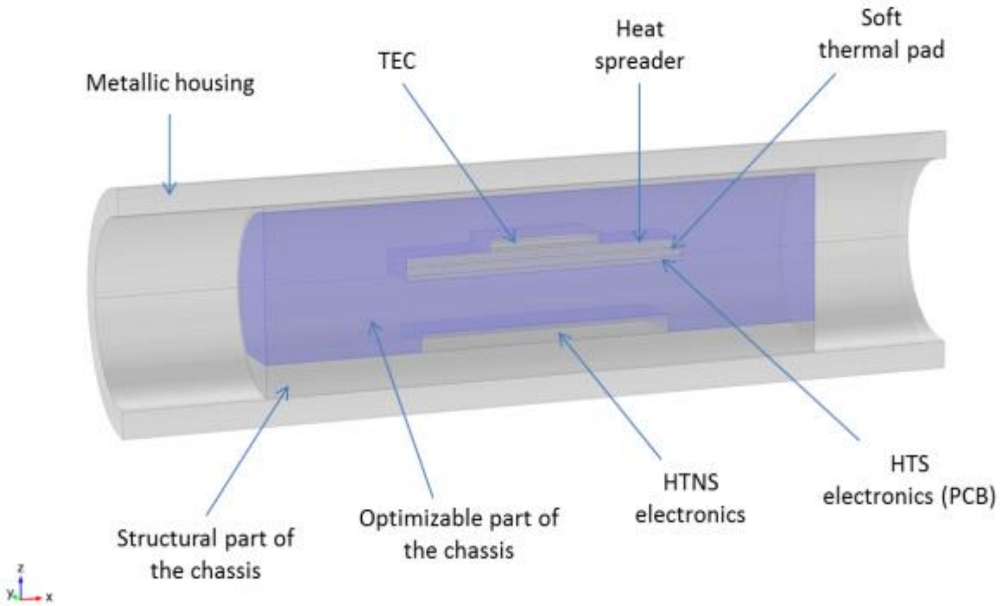
$\Delta T = T_{PCB,design} - T_{PCB,Opt}$

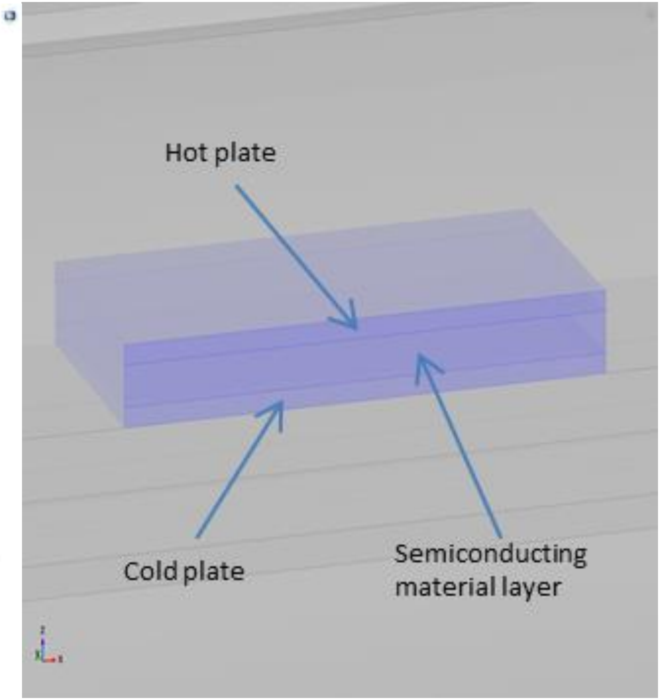
Conclusions

- The topology optimization (SIMP) approach supported the development of a chassis for actively cooled downhole electronics.
- Two main design concepts were found and analyzed.
- A parametric study evaluated the sensitivity of the optimized topologies to the boundary conditions.
- The final design was defined according to the optimization results and proved to perform very closely to the optimized systems.

Thank you for the attention

Extra slides





COMSOL Multiphysics representation of the longitudinal section of the downhole tool (left side) and particular of the TEC device with the two plates and the semiconducting material layer highlighted in blue (right side).

Governing equations

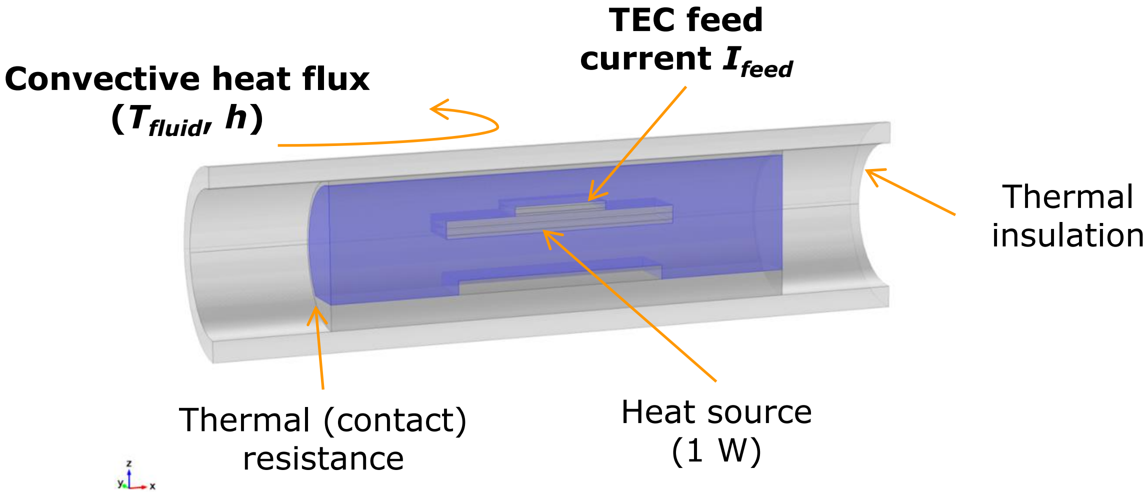
- *Heat conduction* $$\nabla(-k\nabla T) = Q_{source} \qquad (1)$$

Heat Transfer in Solids *(ht)*

- *Modified heat conduction* $$\nabla(\boldsymbol{J}ST - k\nabla T) = Q_{JouleHeating} \qquad (2)$$

Δu Coefficient Form PDE *(c)*

❖ *Boundary conditions*



TEC feed current I_{feed}

Convective heat flux (T_{fluid}, h)

Thermal insulation

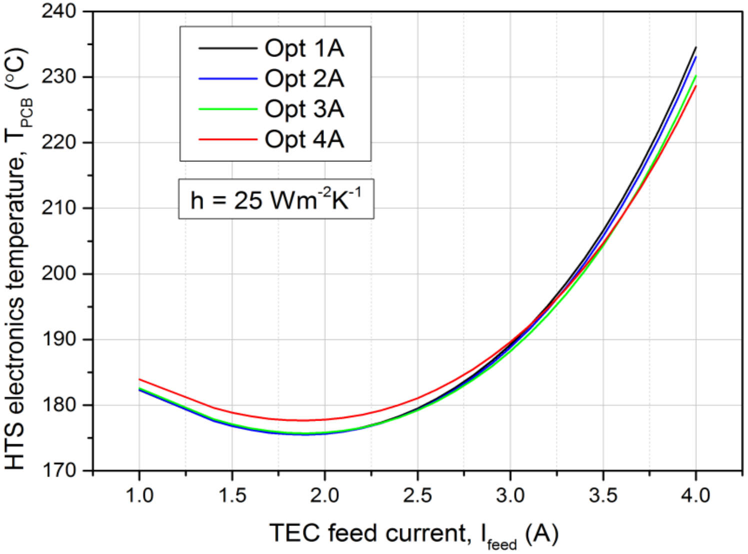
Thermal (contact) resistance

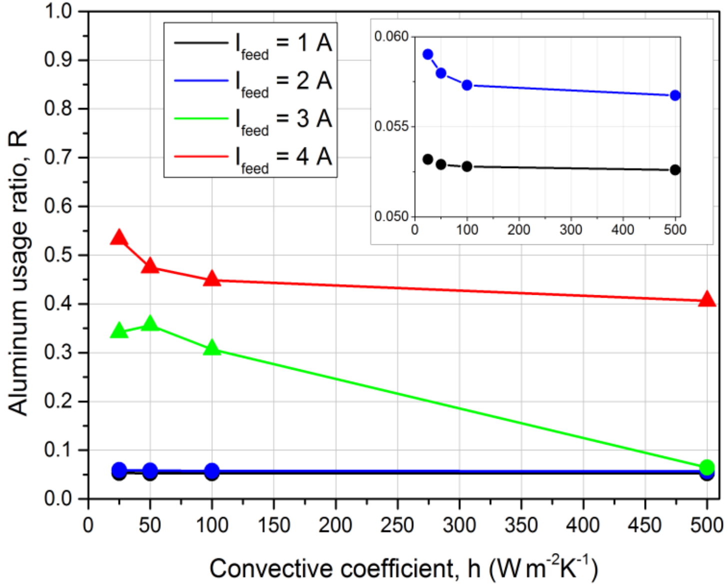
Heat source (1 W)

Cross-Check analysis

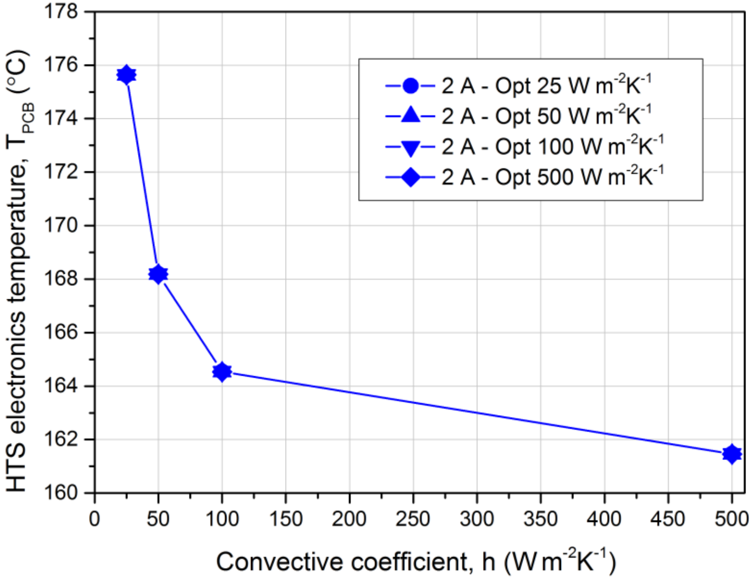
Evaluate the performance of the optimized designs at different boundary conditions

- The optimization process is negligibly sensitive to the well fluid convection regime, at a given I_{feed}.
- The TEC feed current influences significantly the optimized design. But we can control it!
- An optimal feed current $I_{feed,opt}$ was found.
- $I_{feed,opt}$ varies with h and ranges between 2 and 3 A.

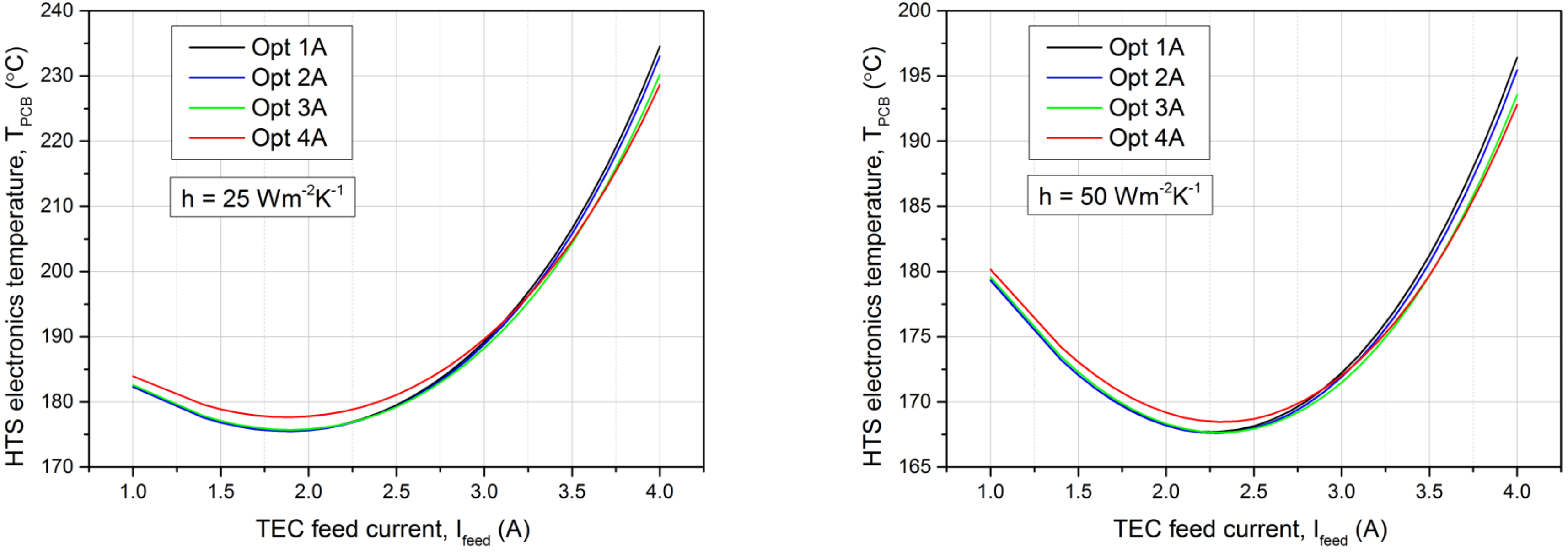




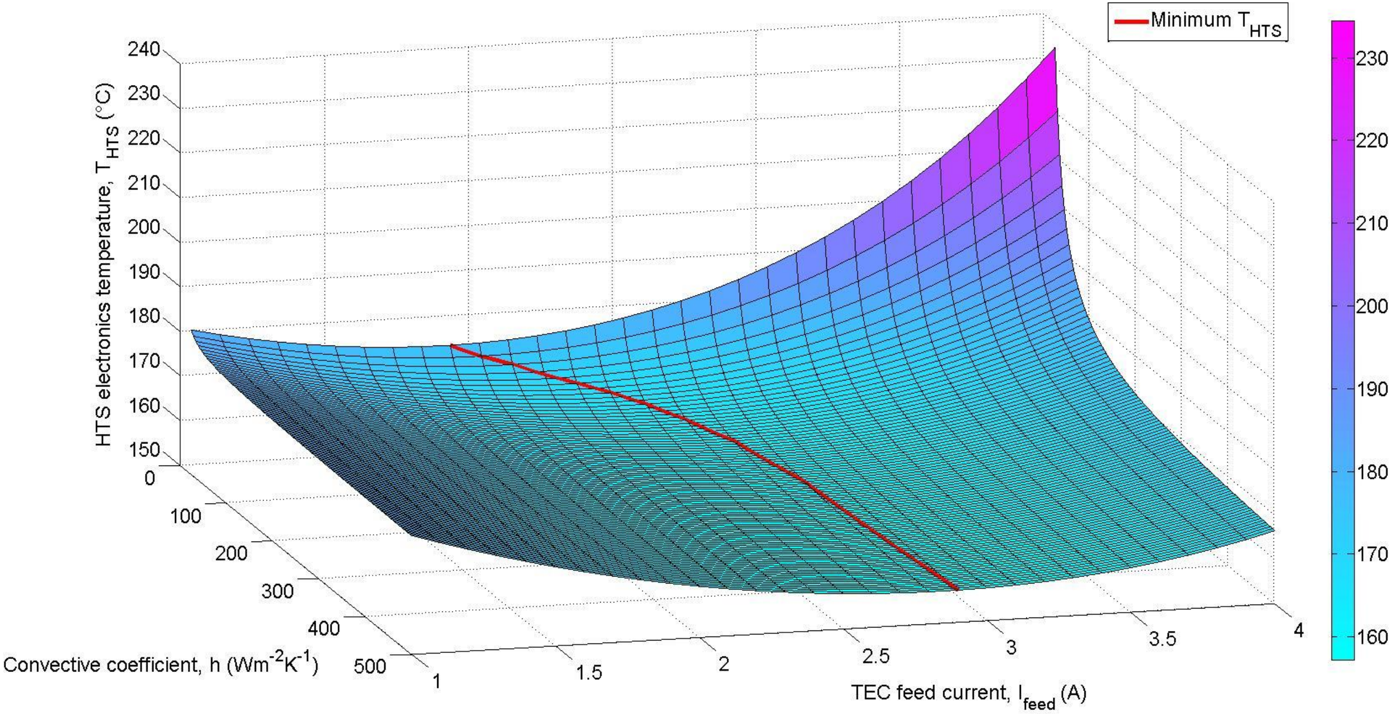
R vs. well fluid convective coefficient, for different TEC feed currents. Different symbols refer to the different optimized design concepts.
● = Design 1, ▲ = Design 2.



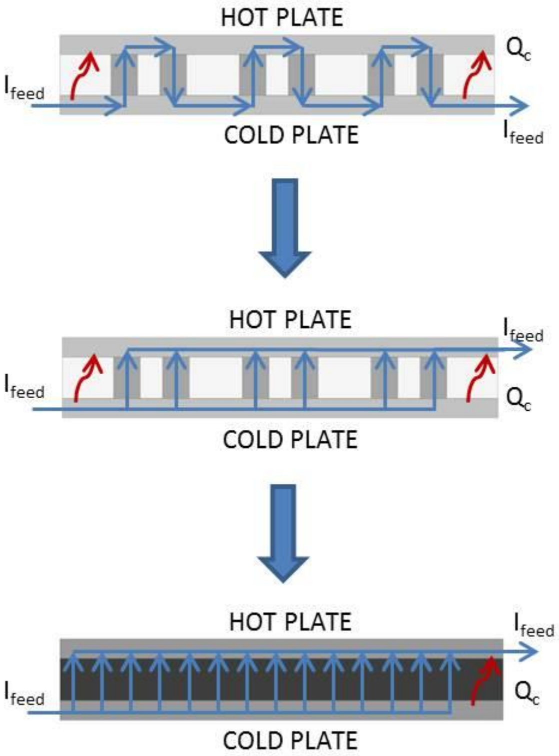
HTS electronics temperature vs. well fluid convective coefficient for four different systems, optimized for I_{feed} = 2 A and h = 25, 50, 100 and 500 Wm^{-2}K^{-1}.



HTS electronics temperature vs. TEC feed current for four different systems, optimized for I_{feed} = 1, 2, 3 and 4 A, and h = 25 Wm^{-2}K^{-1} (left side) and 50 Wm^{-2}K^{-1} (right side).



Characteristic curve of the finally designed electronics unit. The plot reports the performance of the cooling system as HTS electronics temperature vs. Convective coefficient and TEC feed current. The minimum HTS electronics temperatures for each operating condition are highlighted with a red line.



Real case

Intermediate step

Homogeneous model

$$J' = \frac{NI_{feed}}{A_{tot}} = \frac{NI_{feed}}{A_{tot}} \cdot \frac{NA_{leg}}{NA_{leg}} = \frac{I_{feed}}{A_{leg}} \cdot \frac{A_{BiTe}}{A_{tot}} = J\, x_{BiTe}$$

$$\boldsymbol{J}' \cdot S = \boldsymbol{J} \cdot S' \quad \rightarrow \quad S' = S \cdot x_{BiTe}$$

$$k' = k_{air} \frac{A_{air}}{A_{tot}} + k_{BiTe} \frac{A_{BiTe}}{A_{tot}} = k_{air}\,(1 - x_{BiTe}) + k_{BiTe}\, x_{BiTe}$$

$$\sigma' = \sigma_{BiTe}\, x_{BiTe} + \sigma_{air}\, x_{air} = \sigma_{BiTe}\, x_{BiTe}$$

(Gordon 2002)

Topology Optimization Implementation
(SIMP method)

$minimize:$ $$f_{obj}\left(T,\rho_{design}\right)=\frac{1}{A_{PCB}}\int_{\Omega_{PCB}} T\,d\Omega_{PCB} \qquad (3)$$


Optimization *(opt)*

$constraints:$ $$0\leq\rho_{design}\leq 1 \qquad (4)$$


Optimization *(opt)*

$$\boldsymbol{r}\left(T,\rho_{design}\right)=\boldsymbol{0} \qquad (5)$$

$density\ filter:$ $$-r^2\nabla^2\tilde{\rho}+\tilde{\rho}=\rho_{design} \qquad \text{(Lazarov 2011)} \qquad (6)$$


Coefficient Form PDE *(c)*

$projection\ function:$ $$\bar{\tilde{\rho}}_i=\frac{\tanh(\beta\eta)+\tanh(\beta(\tilde{\rho}_i-\eta))}{\tanh(\beta\eta)+\tanh\left(\beta(1-\eta)\right)} \qquad \text{(Wang 2011)} \qquad (7)$$


Analytic 1 *(fun)*

$interpolation\ function:$ $$k_{SIMP}=k_{ins}+(k_{Al}-k_{ins})\bar{\tilde{\rho}}^{\mathrm{p}} \qquad (8)$$

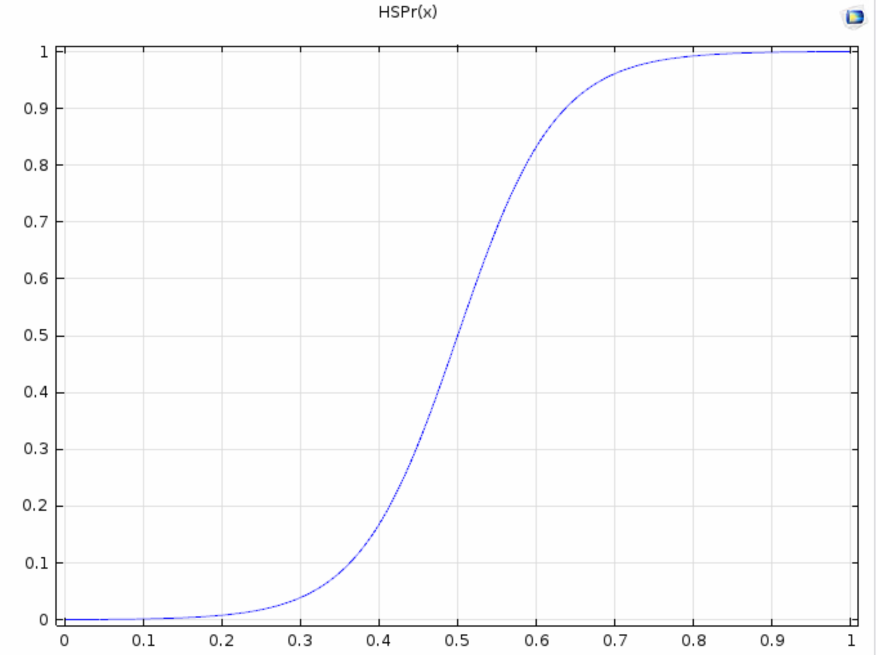

Variables

Topology Optimization Implementation

(SIMP method)

$projection\ function$: $$\bar{\tilde{\rho}}_i = \frac{\tanh(\beta\eta)+\tanh(\beta(\tilde{\rho}_i-\eta))}{\tanh(\beta\eta)+\tanh\big(\beta(1-\eta)\big)}$$ (Wang 2011) (7)

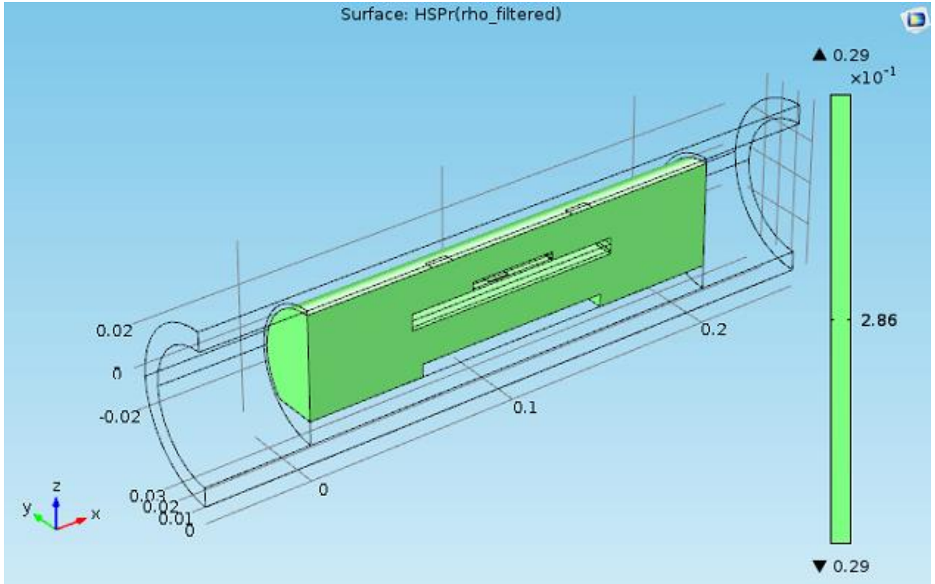

Analytic 1 *(fun)*



Simulation results

$$interpolation\ function: \qquad k_{SIMP} = k_{ins} + (k_{Al} - k_{ins})\bar{\tilde{\rho}}^{\mathrm{p}} \qquad (5)$$


a= Variables


Surface: HSPr(rho_filtered)

Simulation results

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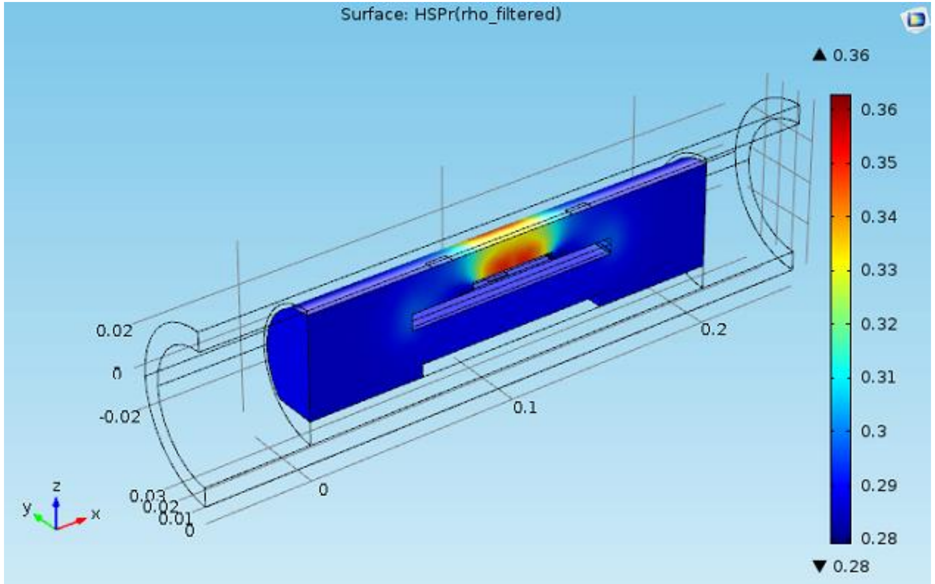
a= Variables



Simulation results

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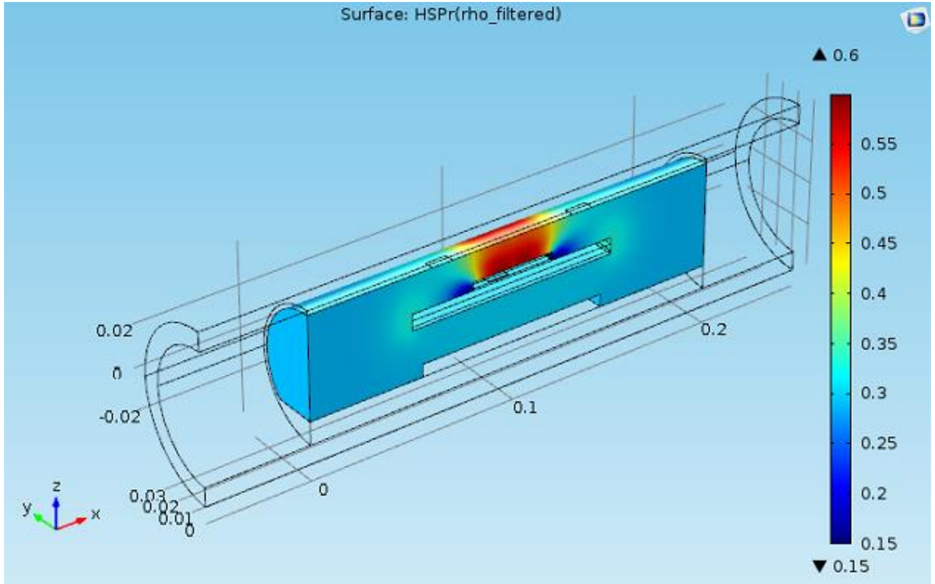
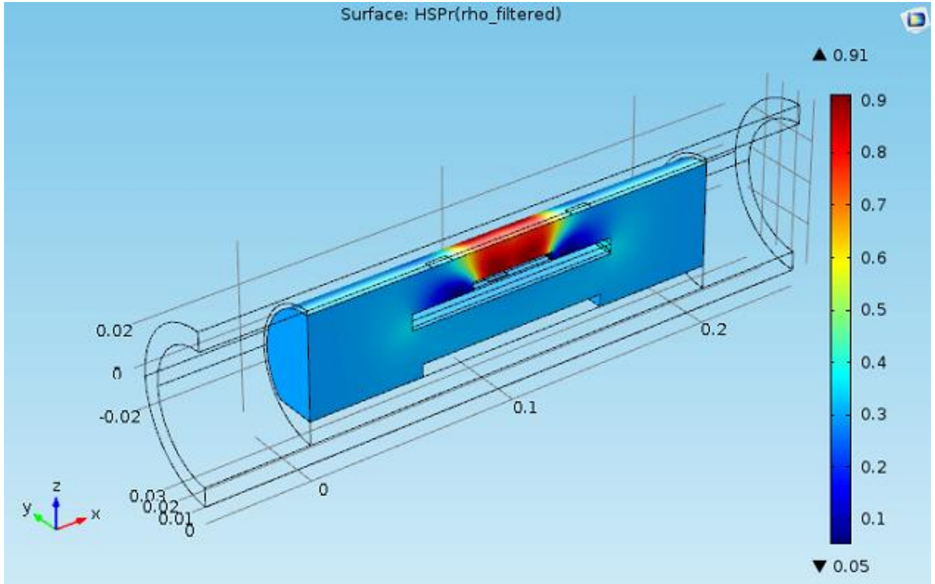


Simulation results

$$\mathit{interpolation\ function}: \qquad k_{SIMP} = k_{ins} + (k_{Al} - k_{ins})\bar{\tilde{\rho}}^{\mathrm{p}} \tag{5}$$

a= Variables



Simulation results

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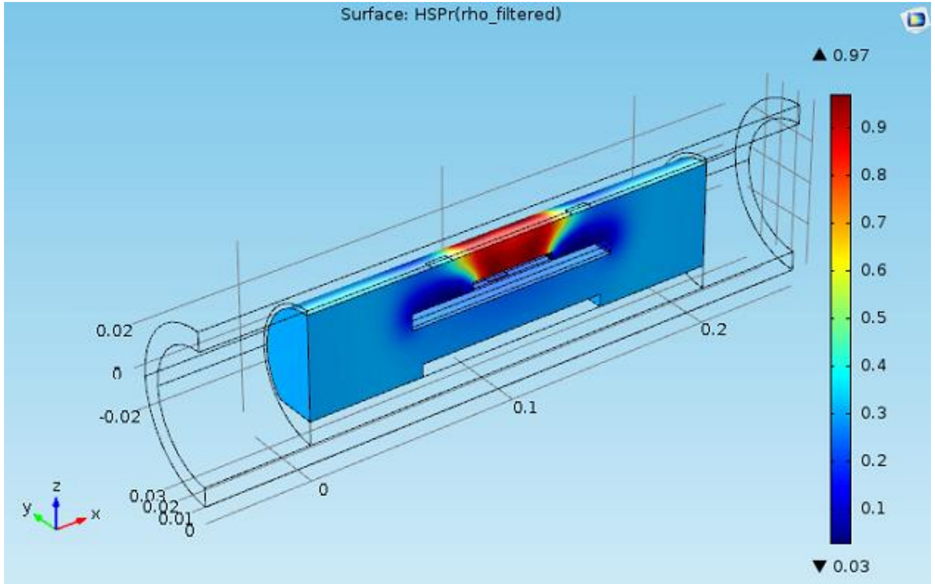

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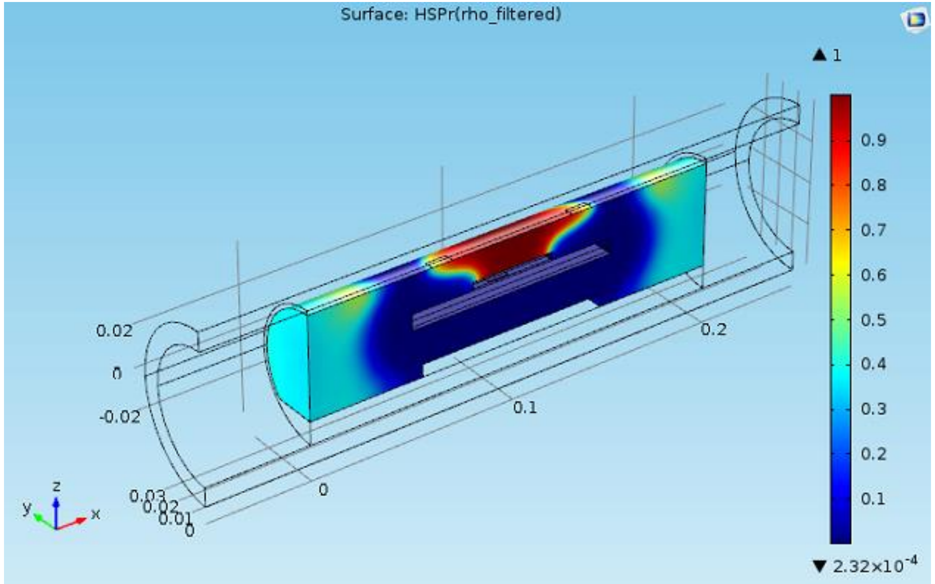

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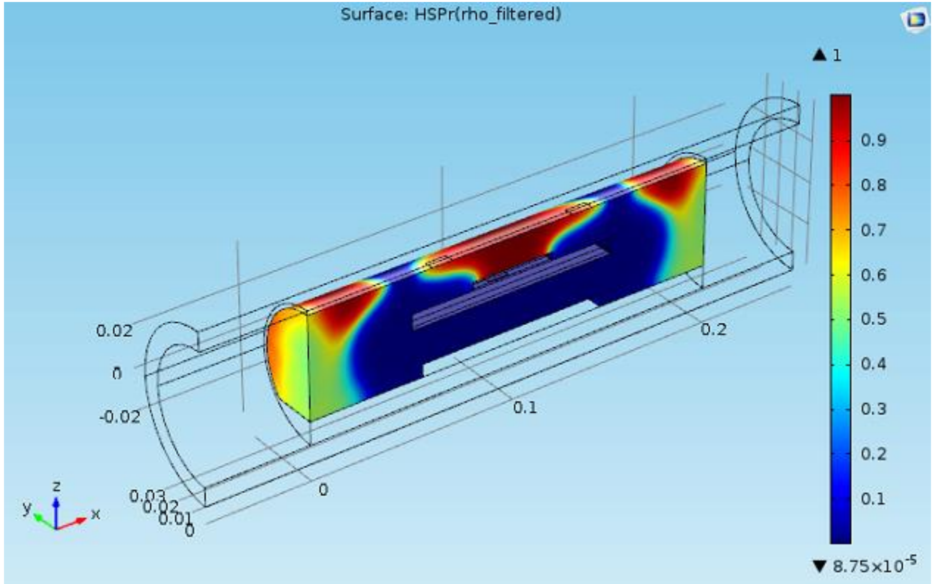

Simulation results

interpolation function: $$k_{SIMP} = k_{ins} + (k_{Al} - k_{ins})\bar{\tilde{\rho}}^{\mathrm{p}} \qquad (5)$$

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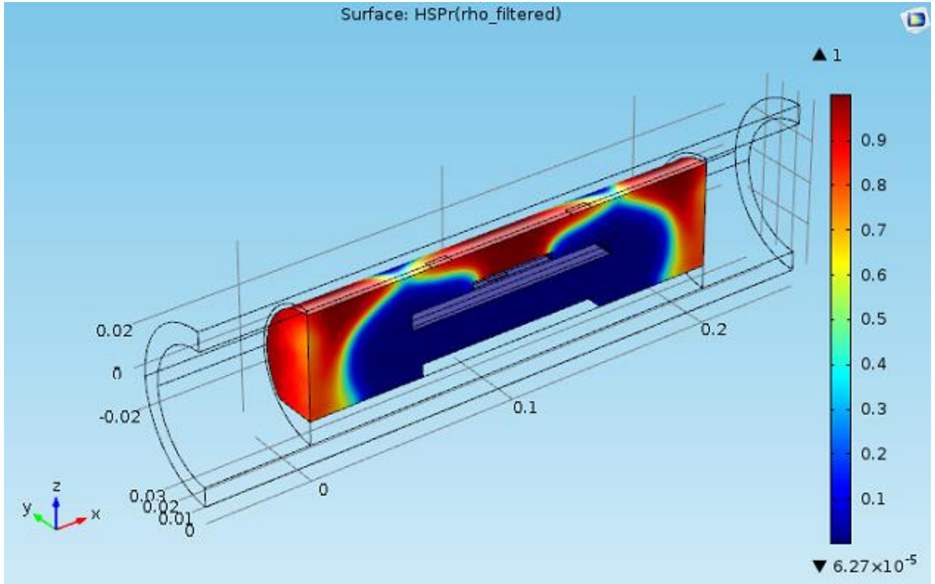
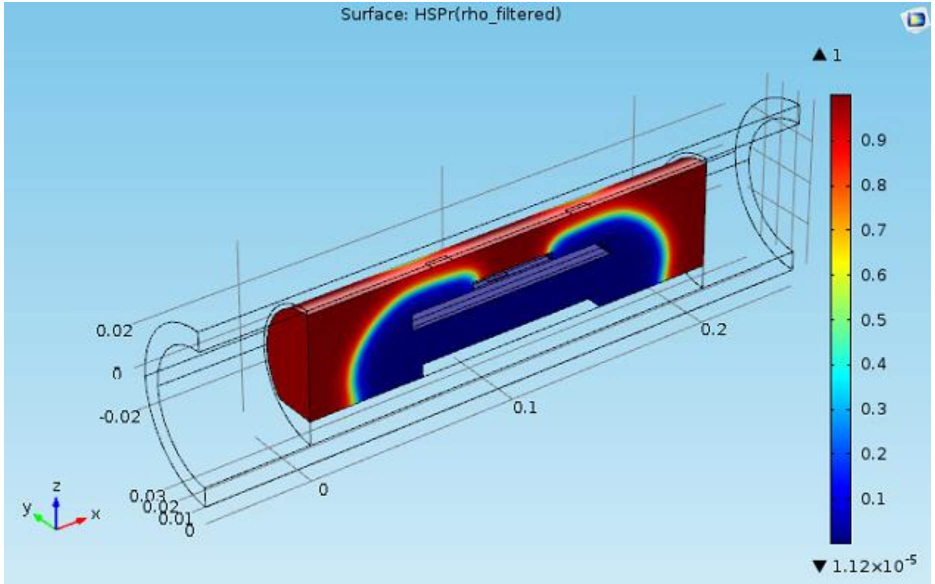
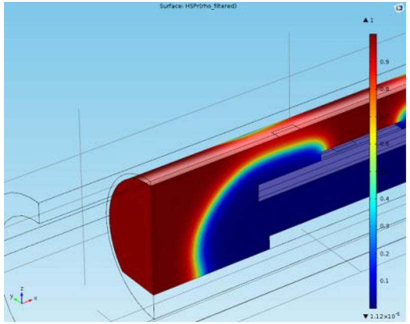


Simulation results

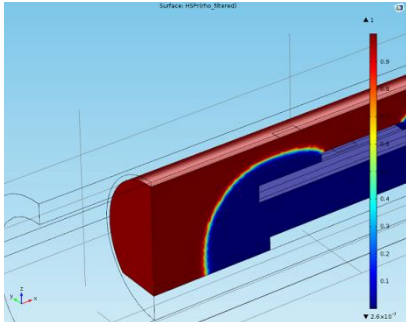
$interpolation\ function$: $k_{SIMP} = k_{ins} + (k_{Al} - k_{ins})\bar{\tilde{\rho}}^{\mathrm{p}}$ (5)

a= Variables





p(η,β = 1)



p(η,β = 8)