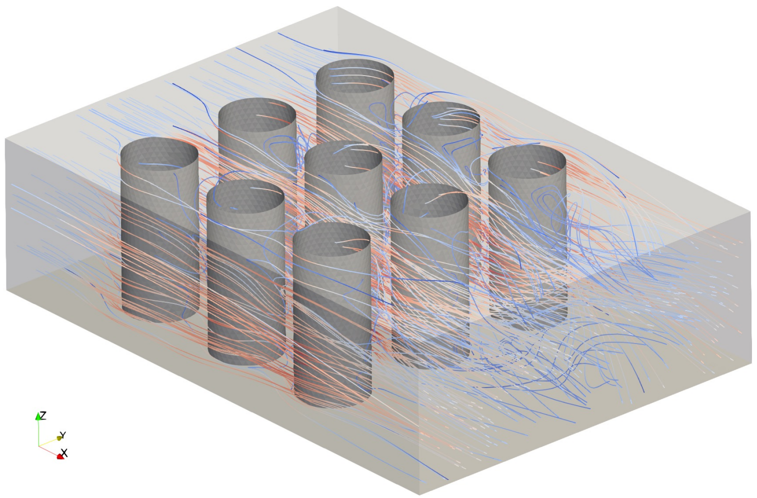
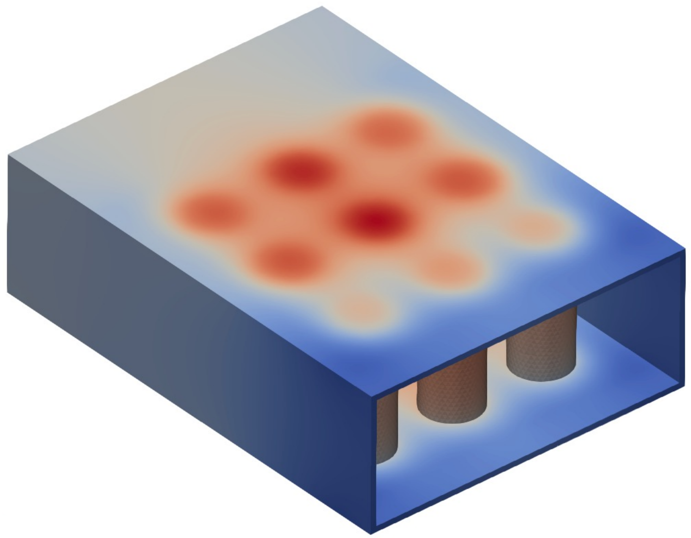
Aerothermal Shape Optimization of Actively-Cooled Battery Packs using Conjugate Heat Transfer





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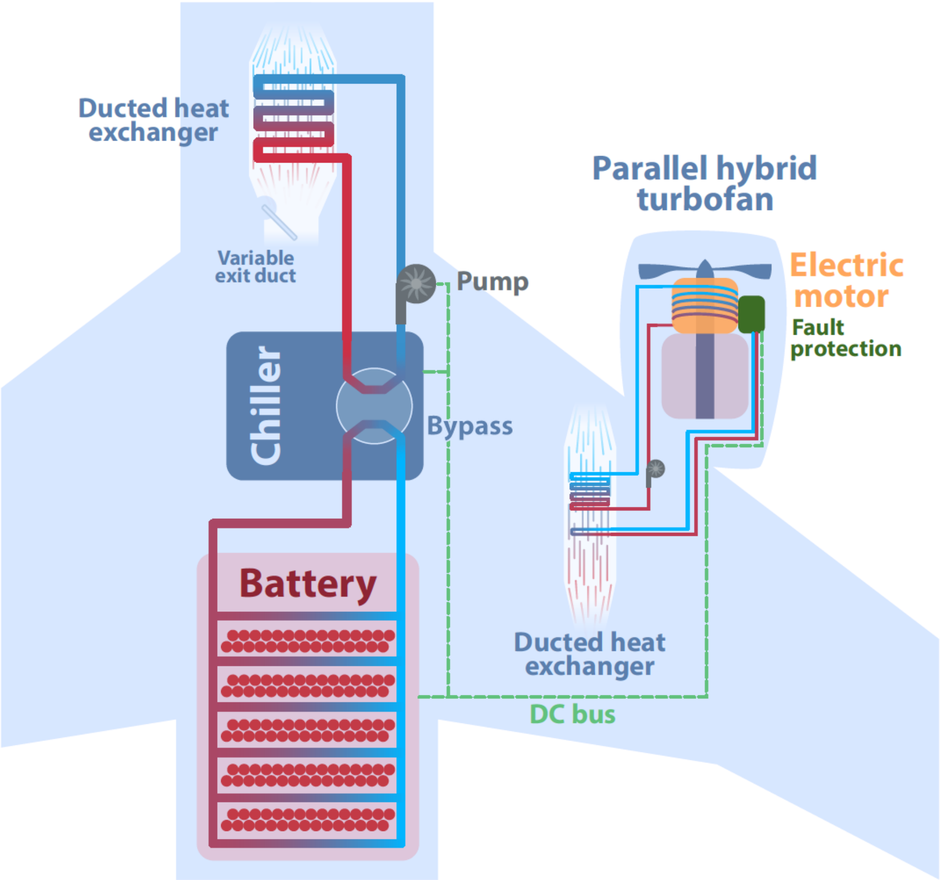
Motivation: Efficient thermal management is needed for electric aircraft's battery systems

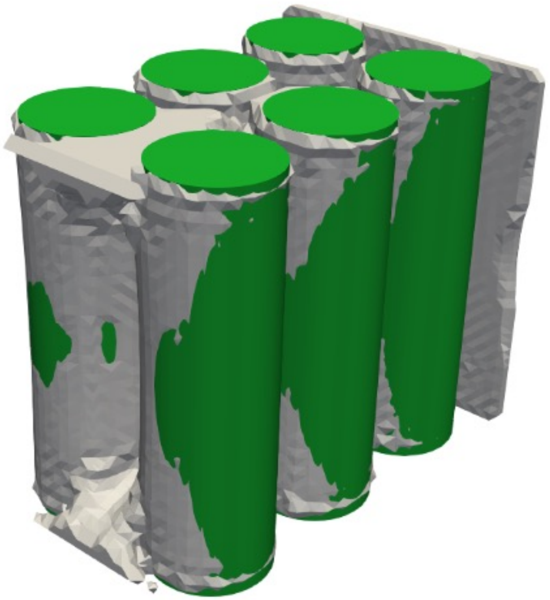


Battery performance for NASA's X-57 electric aircraft concept.
Source: Chin, Schnulo, Miller, Prokopius, and Gray, *AIAA Conf.*, 2019

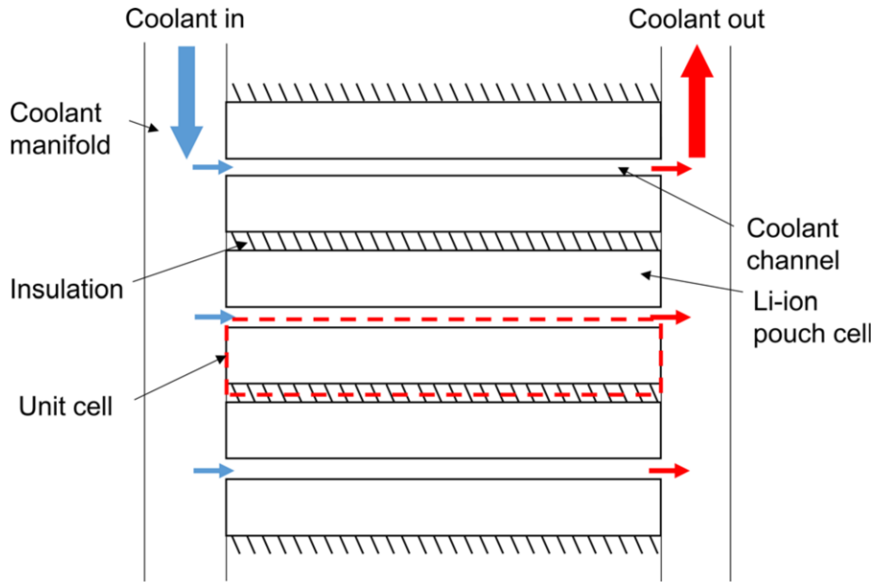
Thermal management for a hybrid aircraft configuration.
Source: Adler, Brelje, and Martins, *Aerospace*, 2022

Literature review: CFD-based aerothermal optimization for battery packs is not well explored

- Chin, Schnulo, Miller, Prokopius, and Gray, *AIAA Conf.*, 2019
- Adler, Brelje, and Martins, *Aerospace*, 2022
- Guibert, Bookwala, Cronk, Meng, and Kim, *AeroBest*, 2023
- Chalise, Shah, Prasher, Jain, *J. Electrochem. En. Conv. Stor*, 2018



Thermo-mechanical topology optimization for battery packs.
Guibert et al., *AeroBest*, 2023



CFD-based aero-thermal analysis for battery packs.
Chalise et al., *J. Electrochem. En. Conv. Stor*, 2018

Objective:

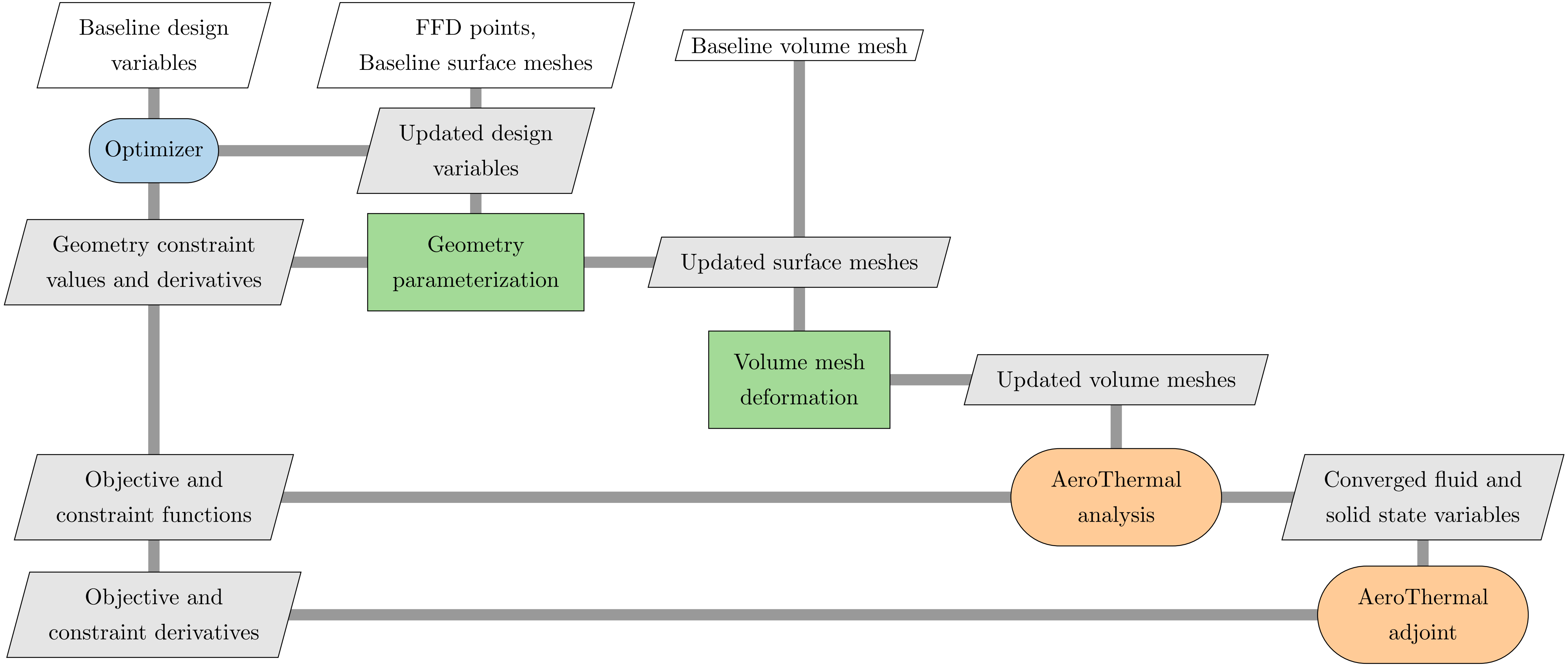
Develop CFD-based aerothermal optimization capability for actively cooled battery packs

Outline

- Motivation and objective
- Aerothermal optimization framework
- Optimization results
- Summary

Aerothermal optimization framework

CFD-based aerothermal optimization framework

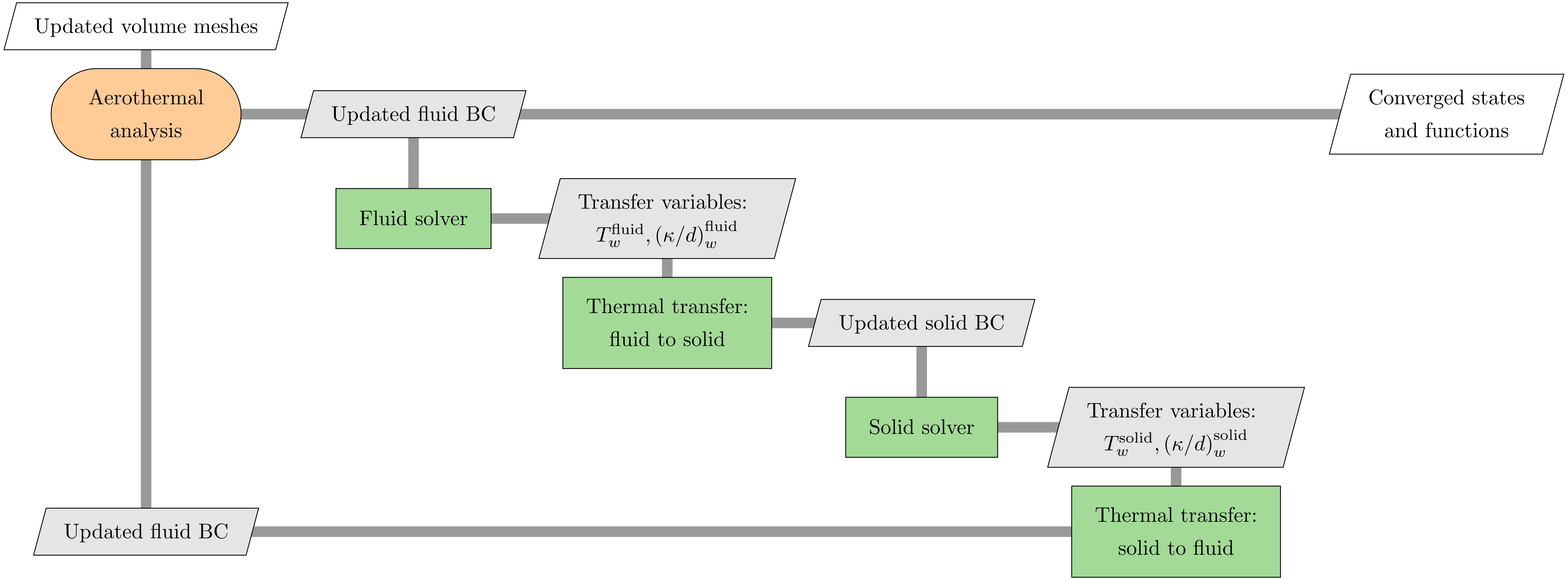


Geometry parameterization (pyGeo):
https://github.com/mdolab/pygeo

Optimization setup (pyOptSparse):
https://github.com/mdolab/pyoptsparse

Volume mesh deformation (IDWarp)
https://github.com/mdolab/idwarp

Aerothermal analysis using the conjugate heat transfer (CHT) method



CFD and heat conduction solvers (OpenFOAM/DAFoam):
https://github.com/mdolab/dafoam

Thermal transfer (FUNtoFEM):
https://github.com/smdogroup/funtofem

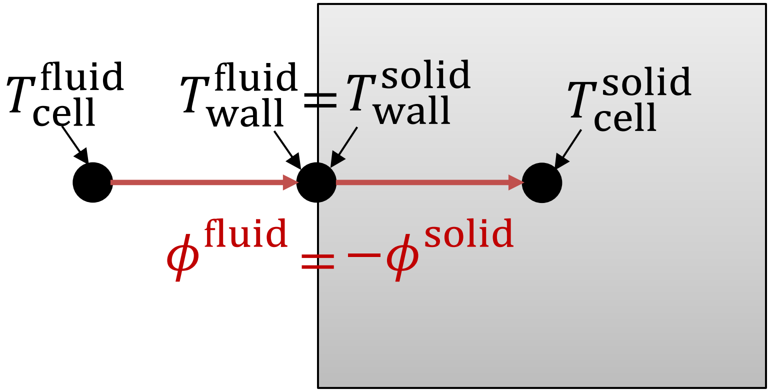
We use a Robin-type BC for the CHT interface to allow the solid to be completely submerged in the fluid

$$T_{\text{wall}} = fT_{\text{ref}} + (1 - f)(T_{\text{cell}} + d\nabla T_{\text{ref}})$$

$$T_{\text{ref}} = T_{\text{cell}}^{\text{neighbor}}, \quad \nabla T_{\text{ref}} = 0, \quad f = C^{\text{neighbor}}/(C^{\text{neighbor}} + C)$$

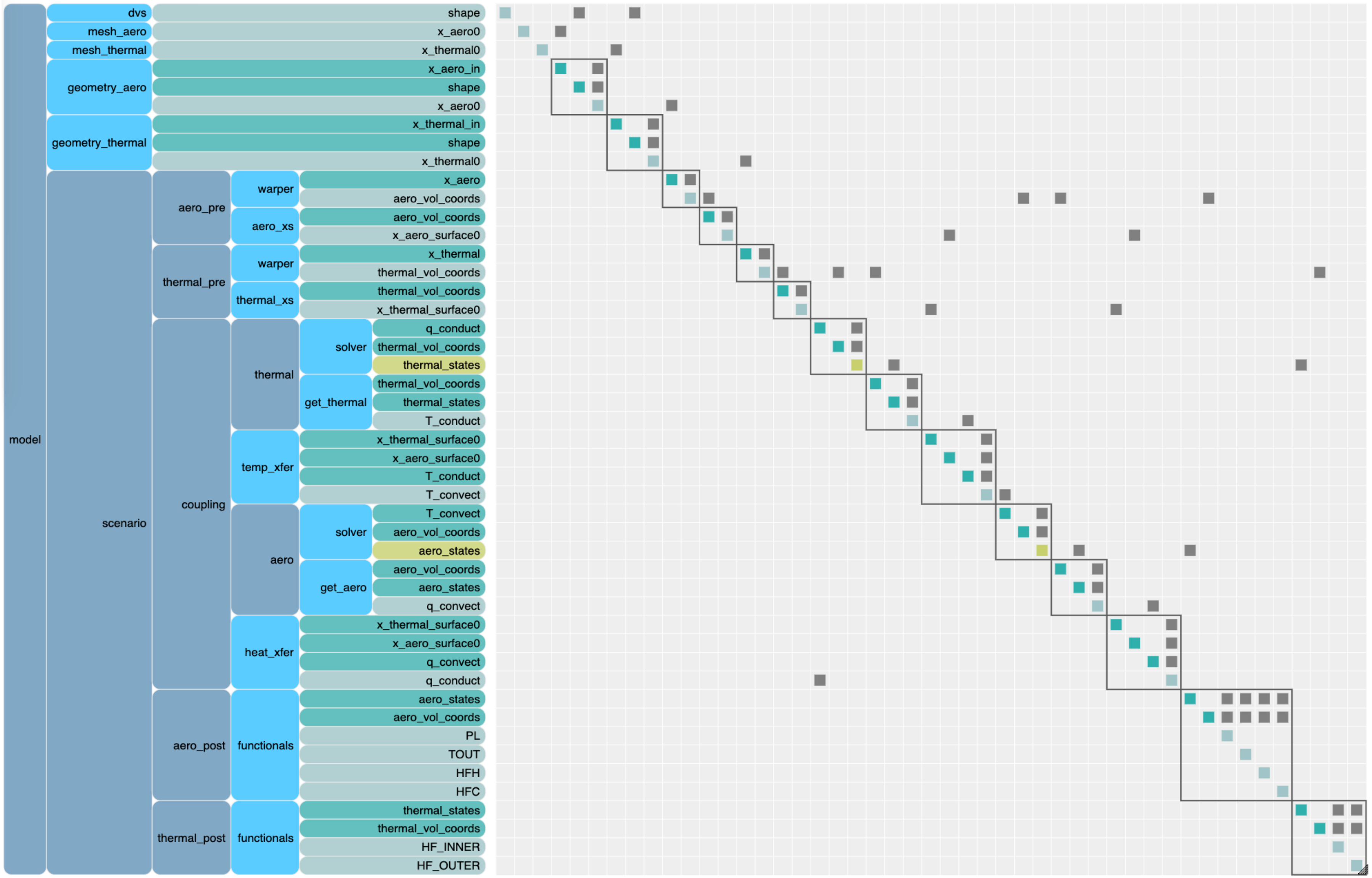
$$T_{\text{wall}}^{\text{solid}} = T_{\text{wall}}^{\text{fluid}} = \frac{C^{\text{solid}}}{C^{\text{solid}} + C^{\text{fluid}}} T_{\text{cell}}^{\text{solid}} + \frac{C^{\text{fluid}}}{C^{\text{solid}} + C^{\text{fluid}}} T_{\text{cell}}^{\text{fluid}}$$

$$\phi^{\text{fluid}} = -\phi^{\text{solid}} = \frac{C^{\text{fluid}} C^{\text{solid}} (T_{\text{cell}}^{\text{fluid}} - T_{\text{cell}}^{\text{solid}})}{C^{\text{fluid}} + C^{\text{solid}}}$$



Schematic of the conjugate heat transfer interface between the fluid (left) and solid (right) domains

We use the OpenMDAO/MPhys framework for the aerothermal coupling



OpenMDAO N2 diagram for the aerothermal optimization

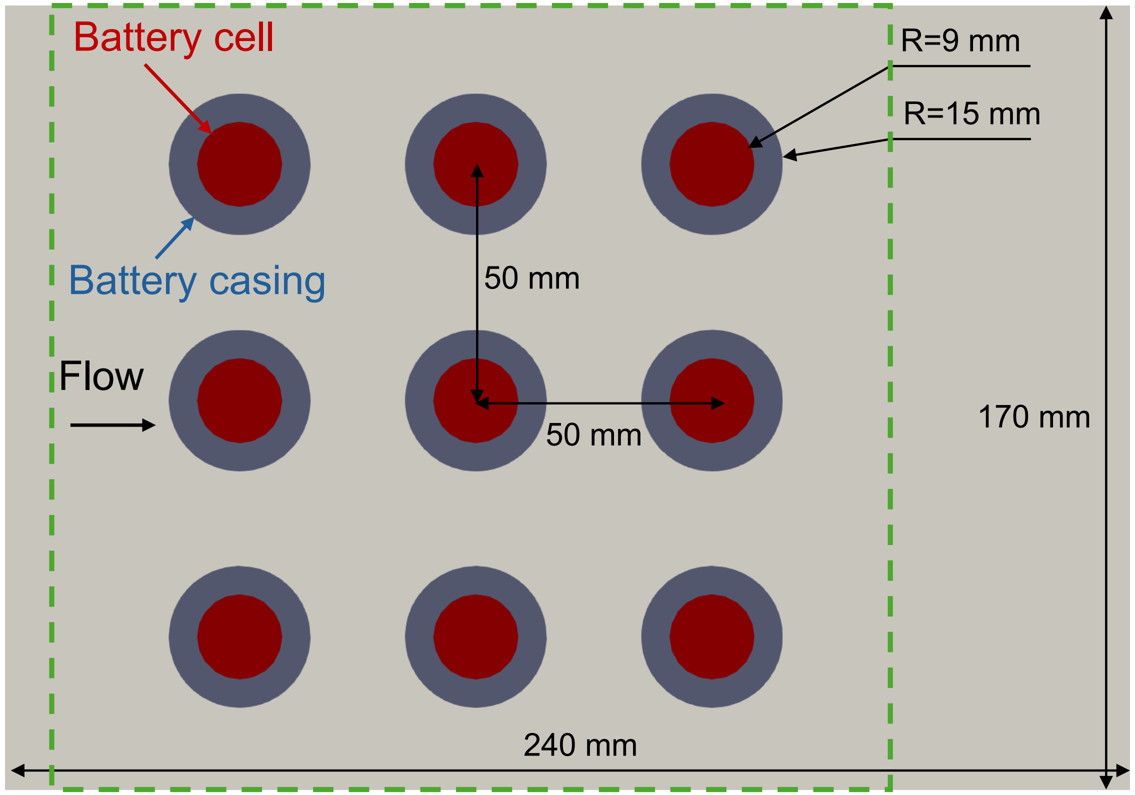
OpenMDAO: github.com/openmdao/openmdao

MPhys: github.com/openmdao/mphys

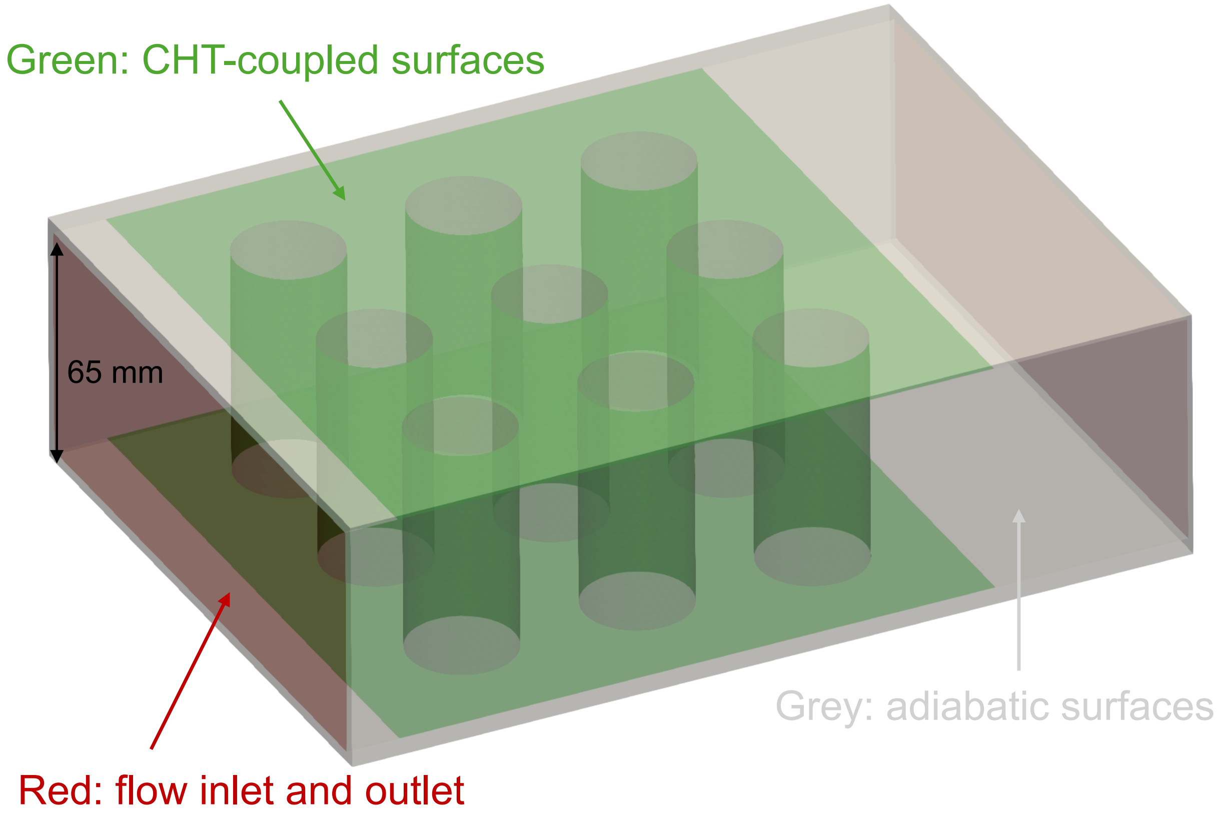
Optimization Results

Schematic of the actively cooled battery pack configuration

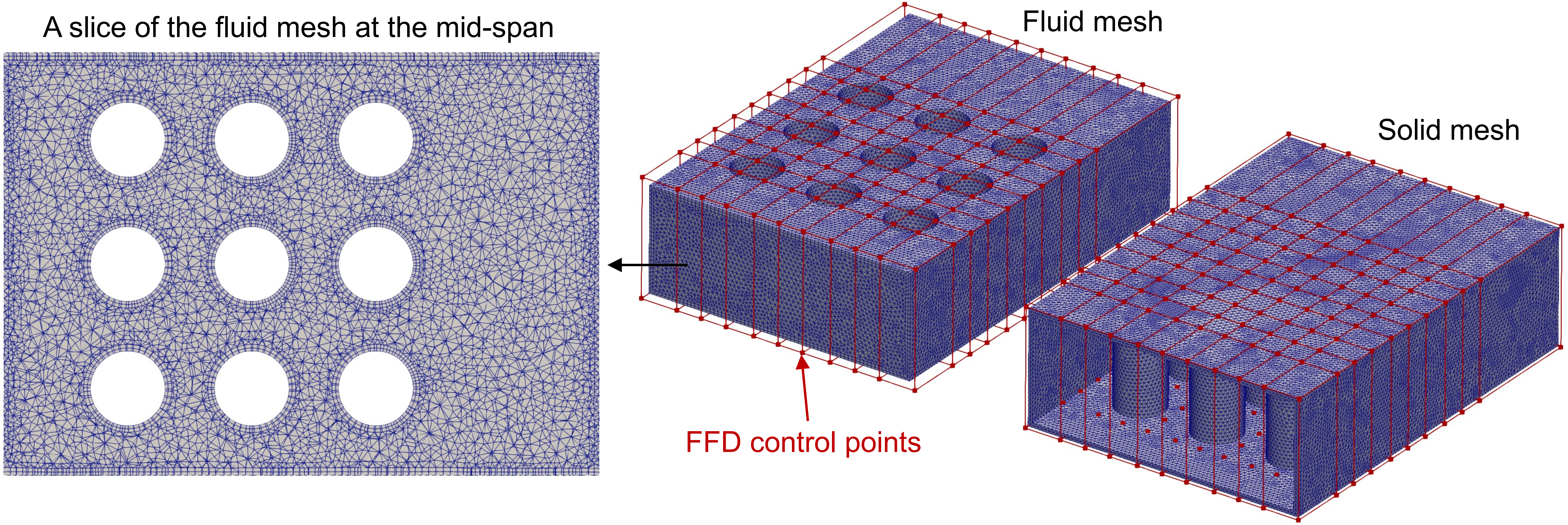
Sectional layout of a 3 by 3 battery pack



3D view of the battery pack



Unstructured meshes for the fluid and solid domains along with the FFD control points

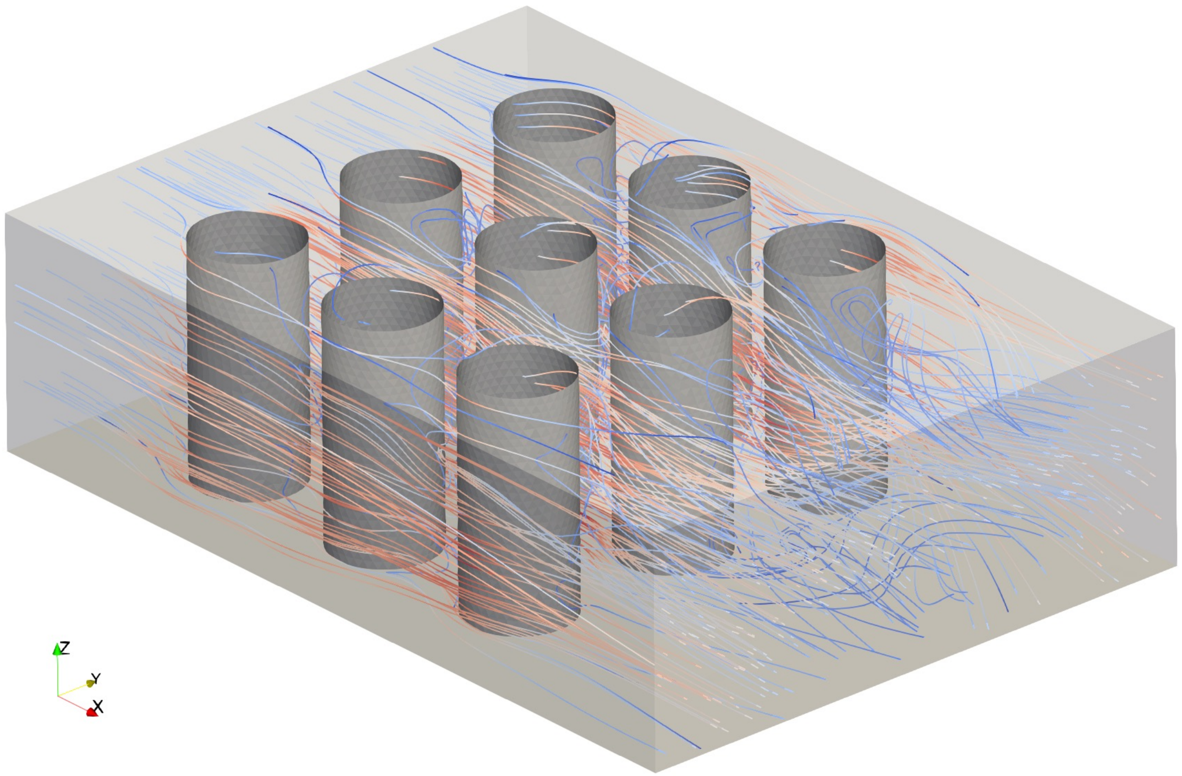


Aerothermal optimization configurations

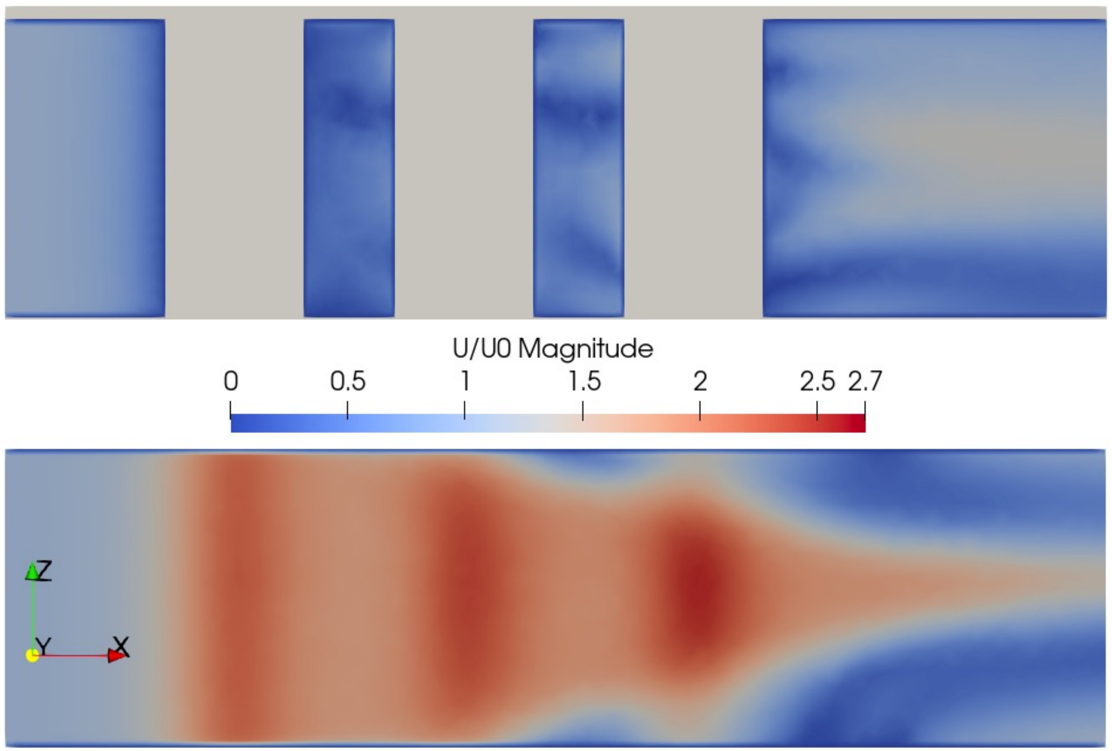
	Function/Variable	Description	Quantity
Minimize	$f = 0.8P/P_{\text{ref}} + 0.2W/W_{\text{ref}}$	Composite function consisting of cooling pump power and battery weight	1
with respect to	$-5 \leq \Delta x \leq 5$ mm	FFD shape displacement in the x direction	4
	$-5 \leq \Delta y \leq 5$ mm	FFD shape displacement in the y direction	3
		Total Design Variables	**7**
subject to	$T_{\text{max}} < 317$ K	Max temperature constraint	1
	$\theta_{\text{fluid}} \leq 75°$	Max mesh non-orthogonality for fluid	1
	$\mu_{\text{fluid}} \leq 5$	Max mesh skewness for fluid	1
	$\theta_{\text{solid}} \leq 75°$	Max mesh non-orthogonality for fluid	1
	$\mu_{\text{solid}} \leq 5$	Max mesh skewness for fluid	1
	$r \geq 10$ mm	Min radius constraint	1
		Total Constraint Functions	**6**

Velocity contour and streamline for the baseline design

3D streamline

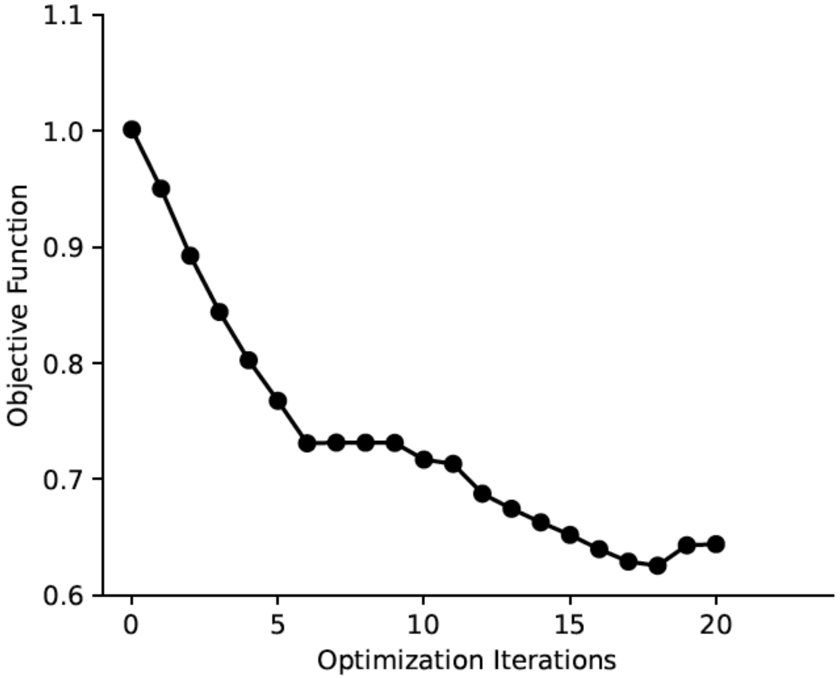


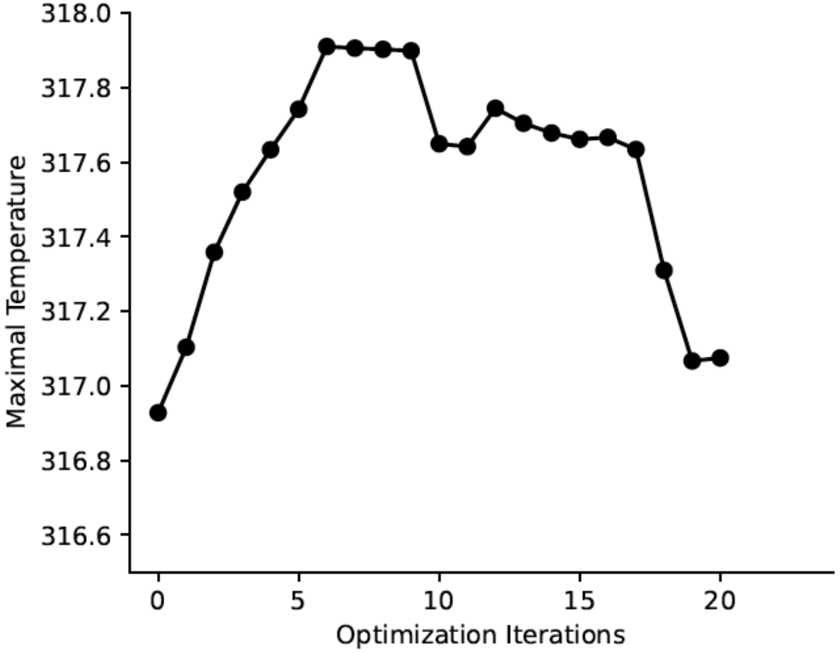
Velocity contour



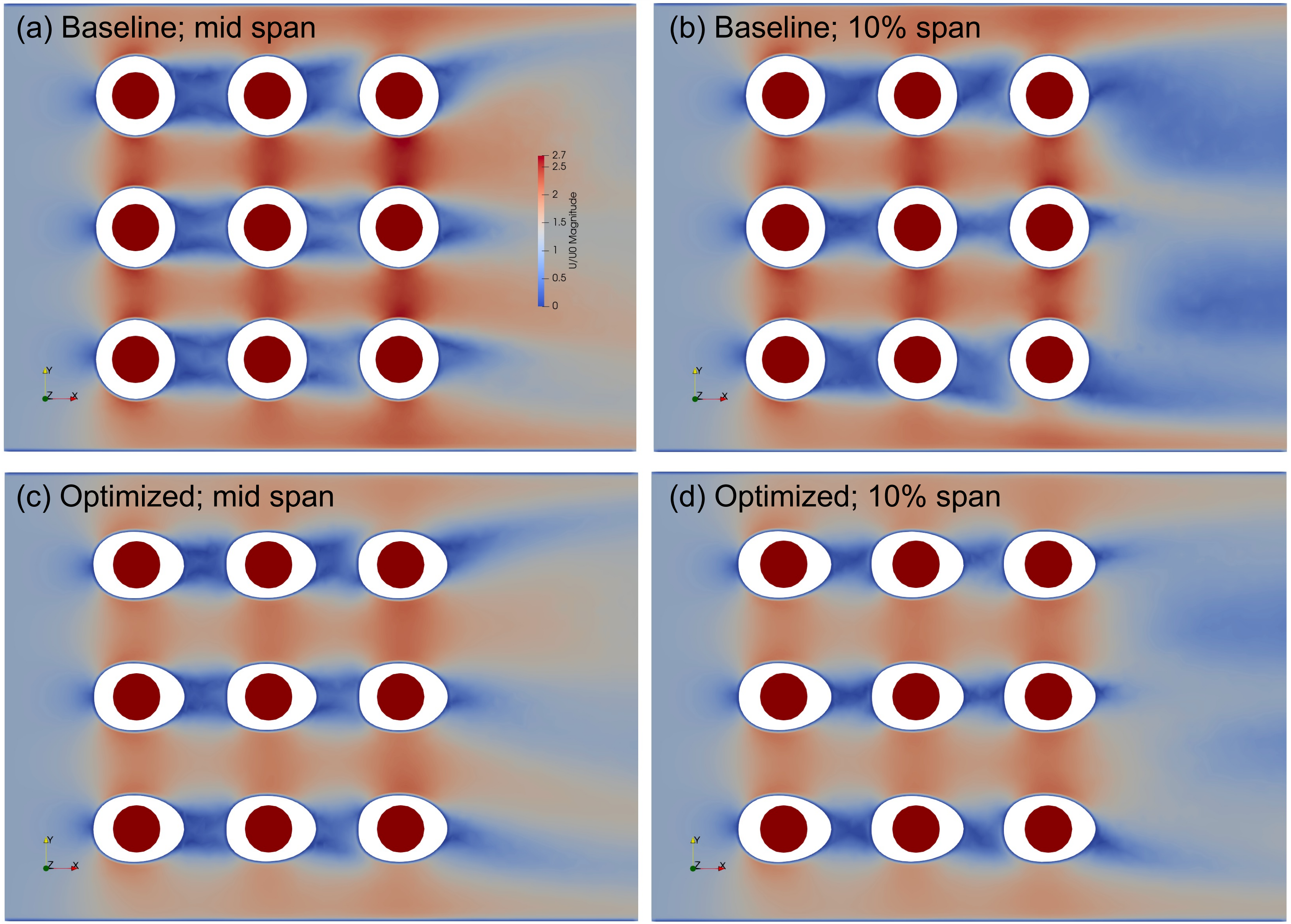
The optimized design reduced the pump power and battery weight while satisfying the temperature constraint

	Pump power	Battery weight	Max temperature
Baseline	1.000	1.000	316.93
Optimized	0.554	0.985	317.07
Difference	↓ 44.6%	↓ 1.5%	↑ 0.04%

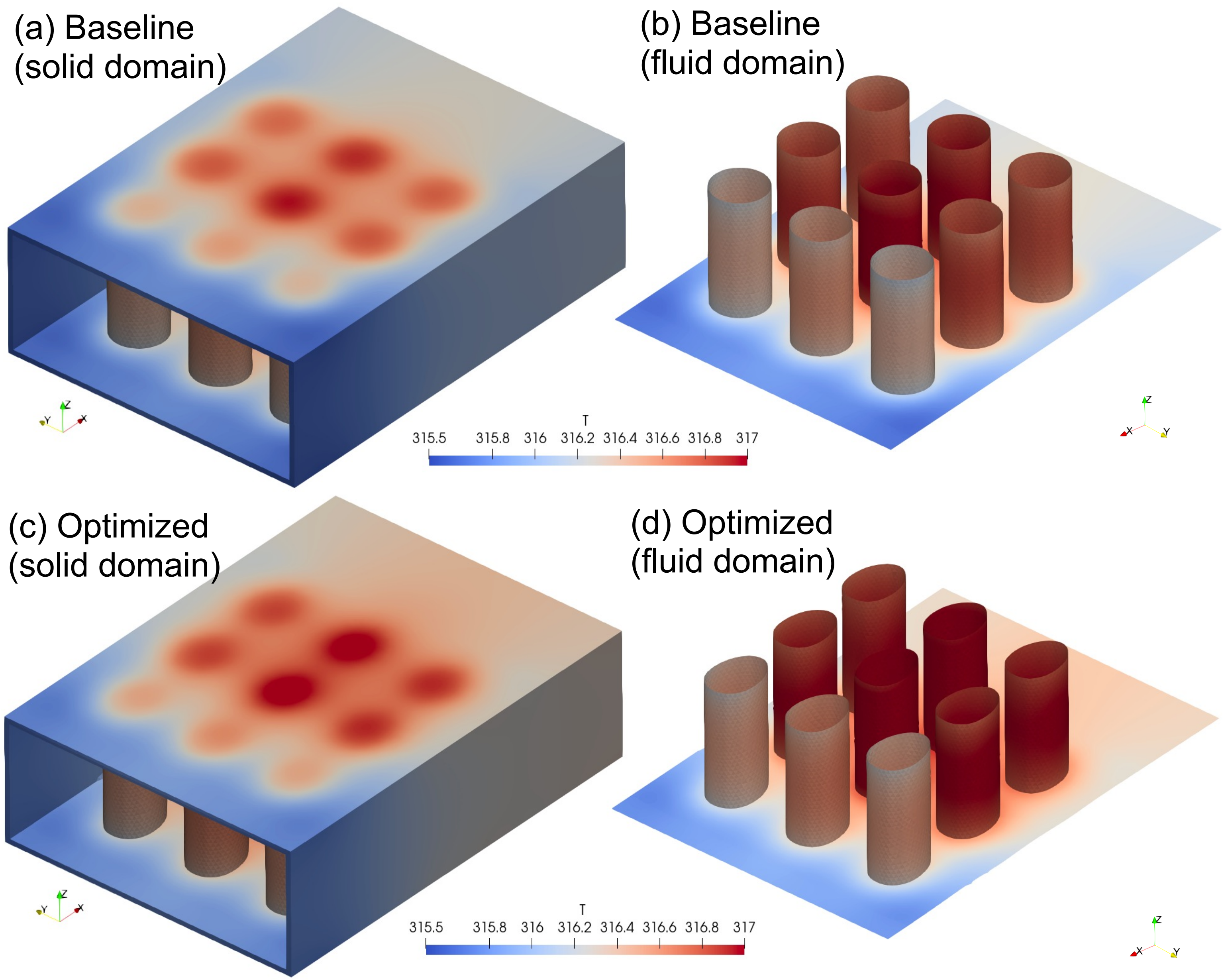




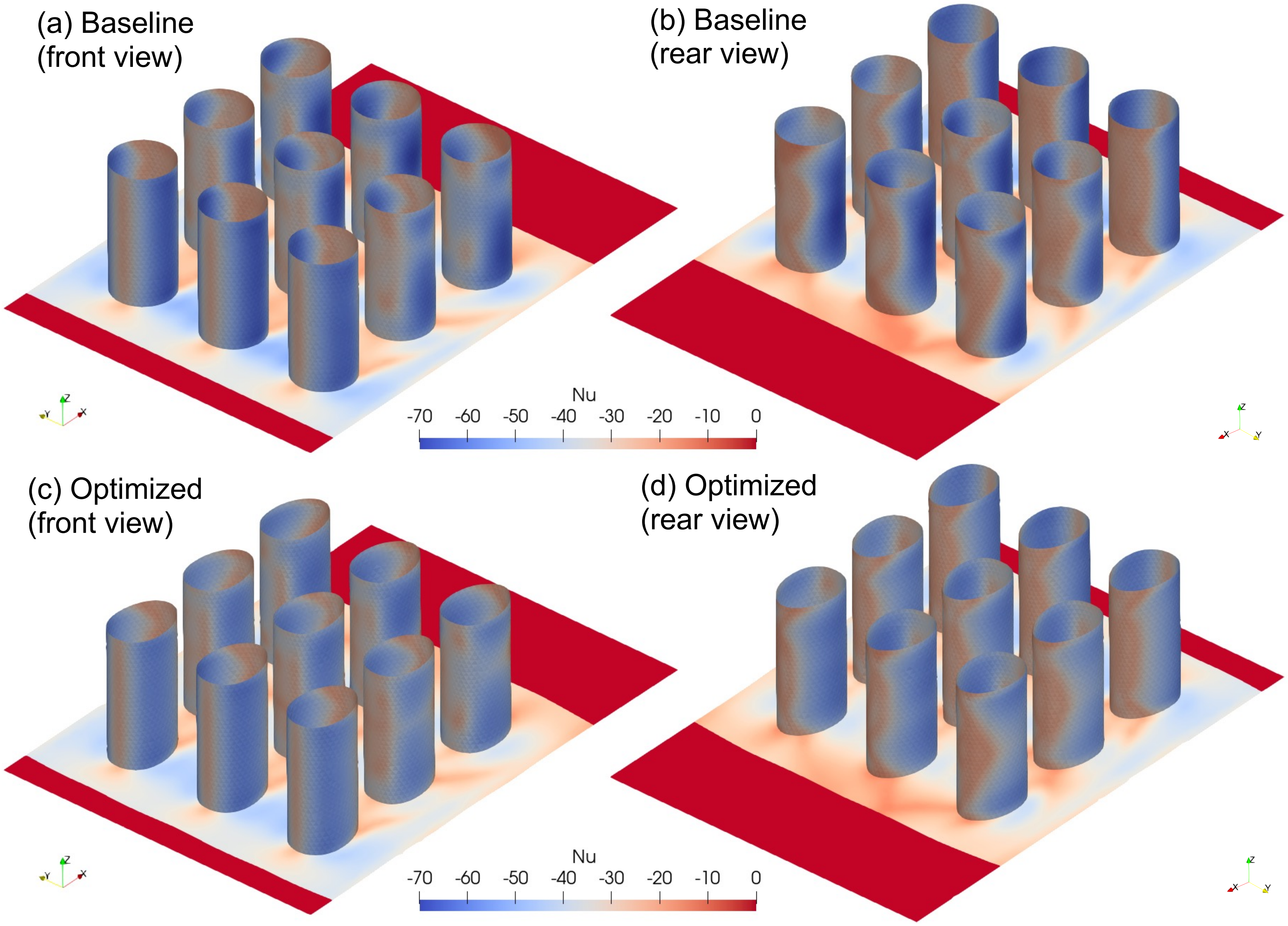
Velocity contours at different spanwise locations



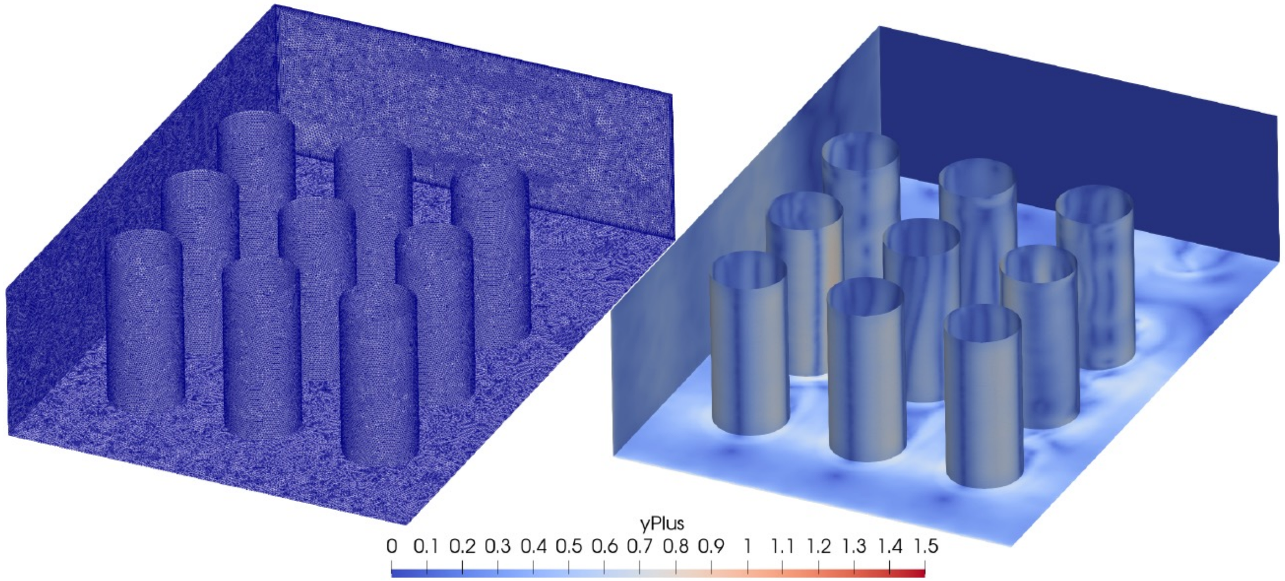
Temperature contours for the fluid and solid domains

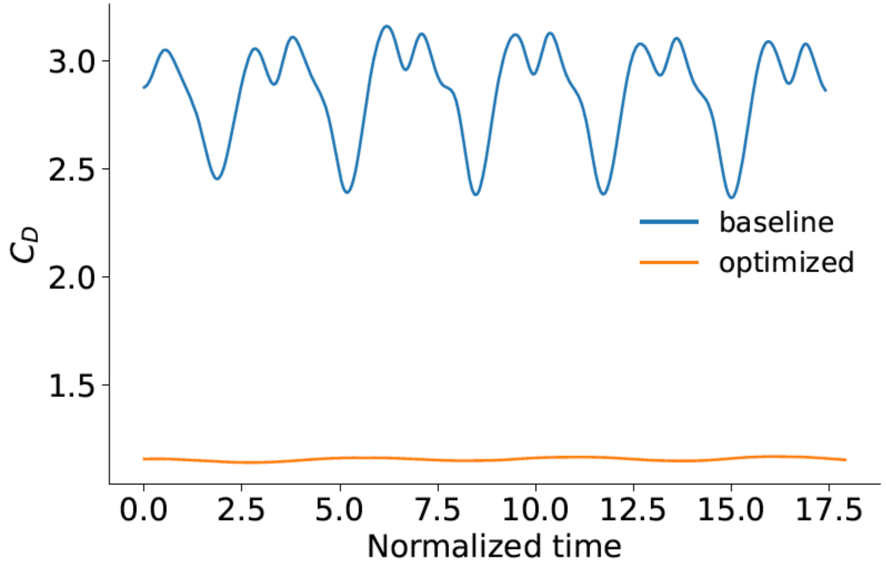


Nusselt number contours from different view angles



Error quantification for using coarse-mesh CFD





	Pressure loss (Pa)	Transferred heat (W)
Baseline (coarse mesh)	90.2	89.8
Optimized (coarse mesh)	50.0	89.6
Difference	↓ 44.6%	↓ 0.2%
Baseline (fine mesh)	105.6	107.9
Optimized (fine mesh)	48.7	95.5
Difference	↓ 53.9%	↓ 11.5%

Summary

- We developed the aerothermal optimization capability under OpenMDAO for actively cooled battery pack designs.
- The optimized design reduced the pump power and battery weight while satisfying the maximal temperature constraint.
- This work has the potential to accelerate the design of high-performance thermal management systems for electric aircraft.

Thank You!

We acknowledge the funding support provided by the National Aeronautics and Space Administration Established Program to Stimulate Competitive Research (NASA-EPSCoR) under Grant No. 80NSSC23M0159.