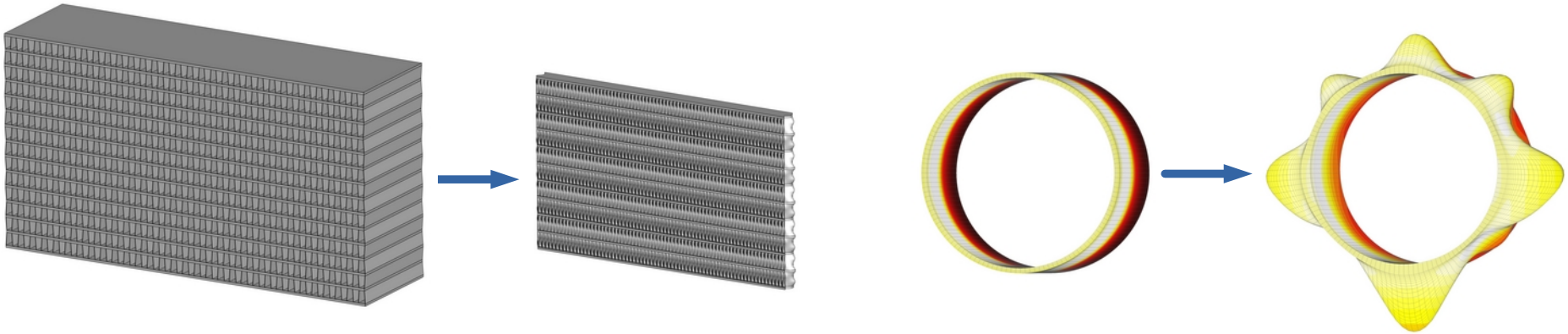
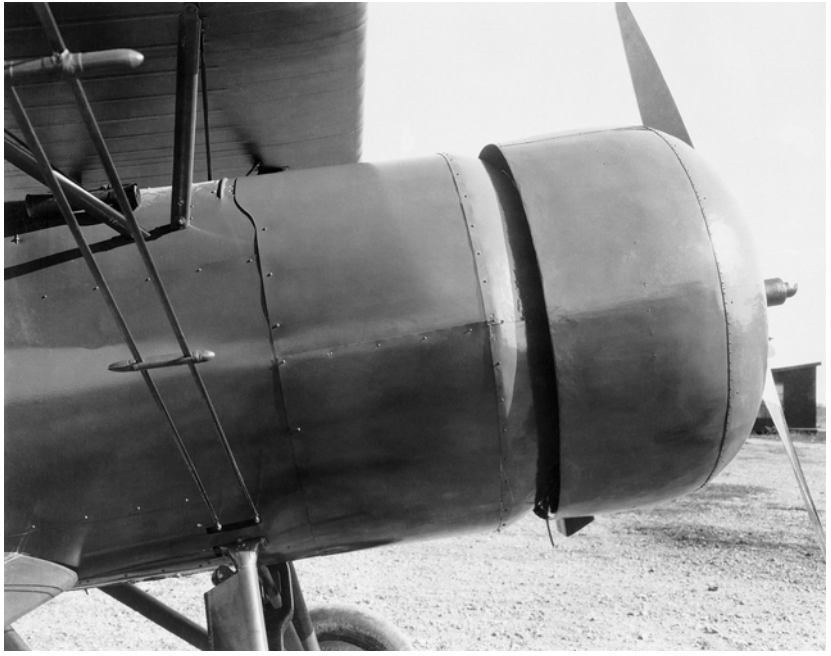
Aerodynamic Shape Optimization of Heat Exchangers



Josh Anibal, Joaquim R. R. A. Martins
University of Michigan
Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, July 20th, 2023

Cooling engines is a historic problem in aviation



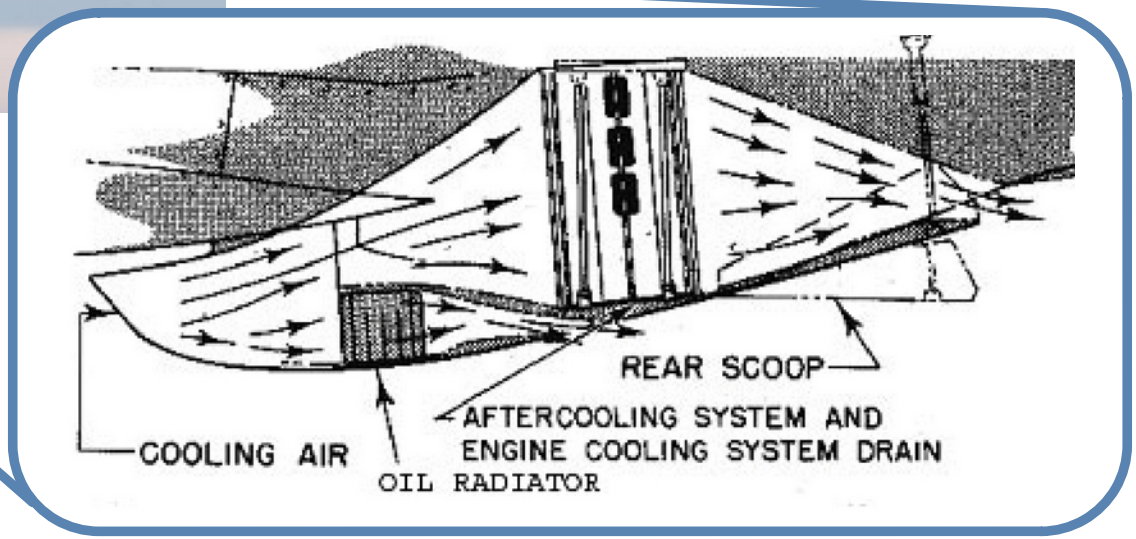
NACA cowling



surface heat exchangers

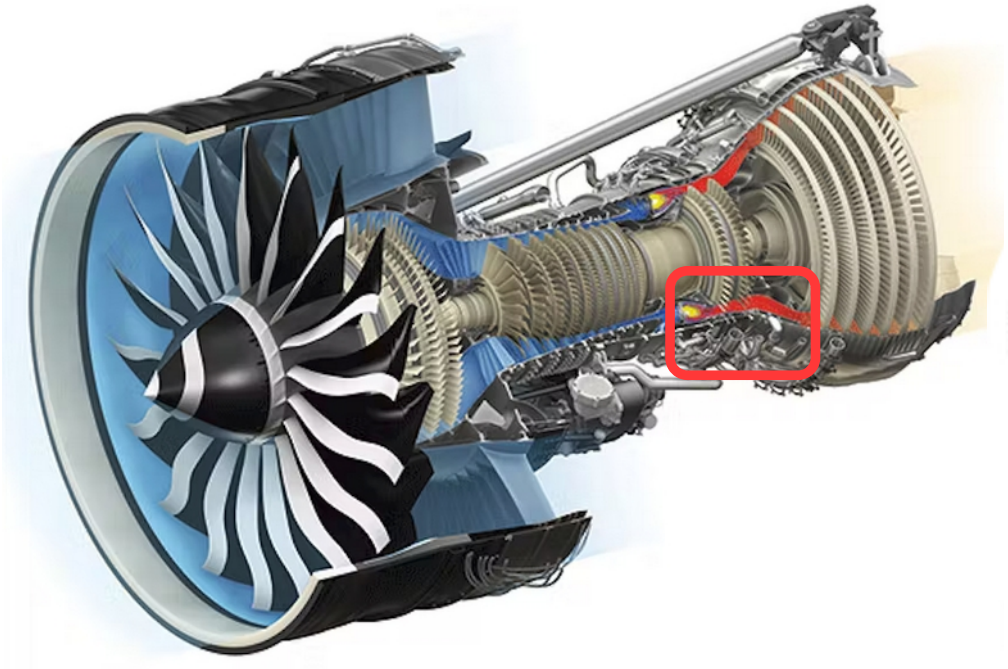
Compact heat exchangers were developed for WWII planes

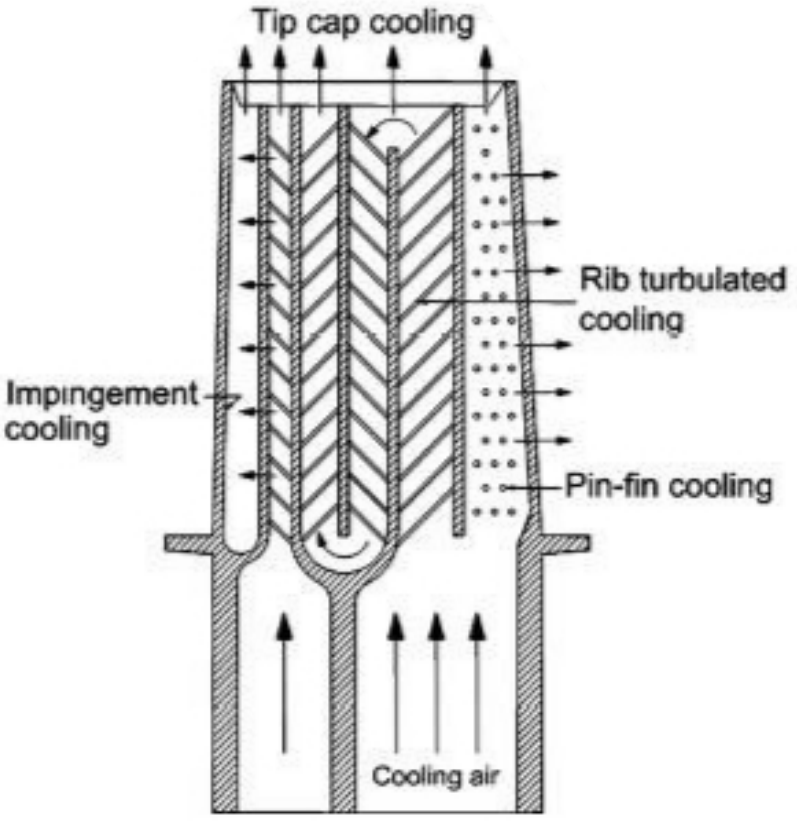




P-58 radiator scoop

The cooling needs changed with jet engines





Ghazali, and Rahim.,
CFD prediction of heat and fluid flow through U-bends using high reynolds-number EVM and DSM models, 2013

New propulsion will again lead to new aircraft concepts

Vahana



HY4



X-57



Spirit of Innovation

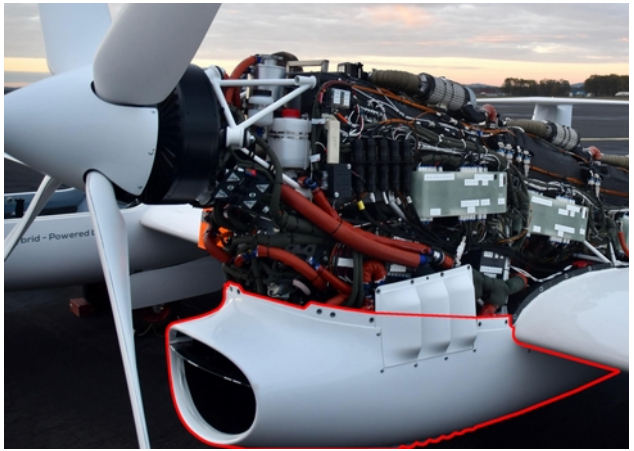


Next-gen aircraft will rely on heat exchangers

Vahana



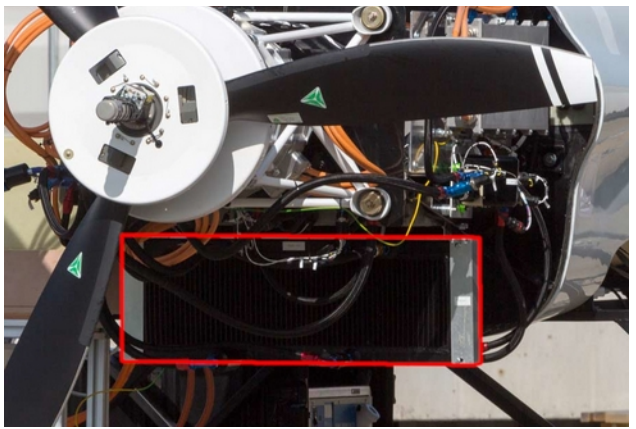
HY4



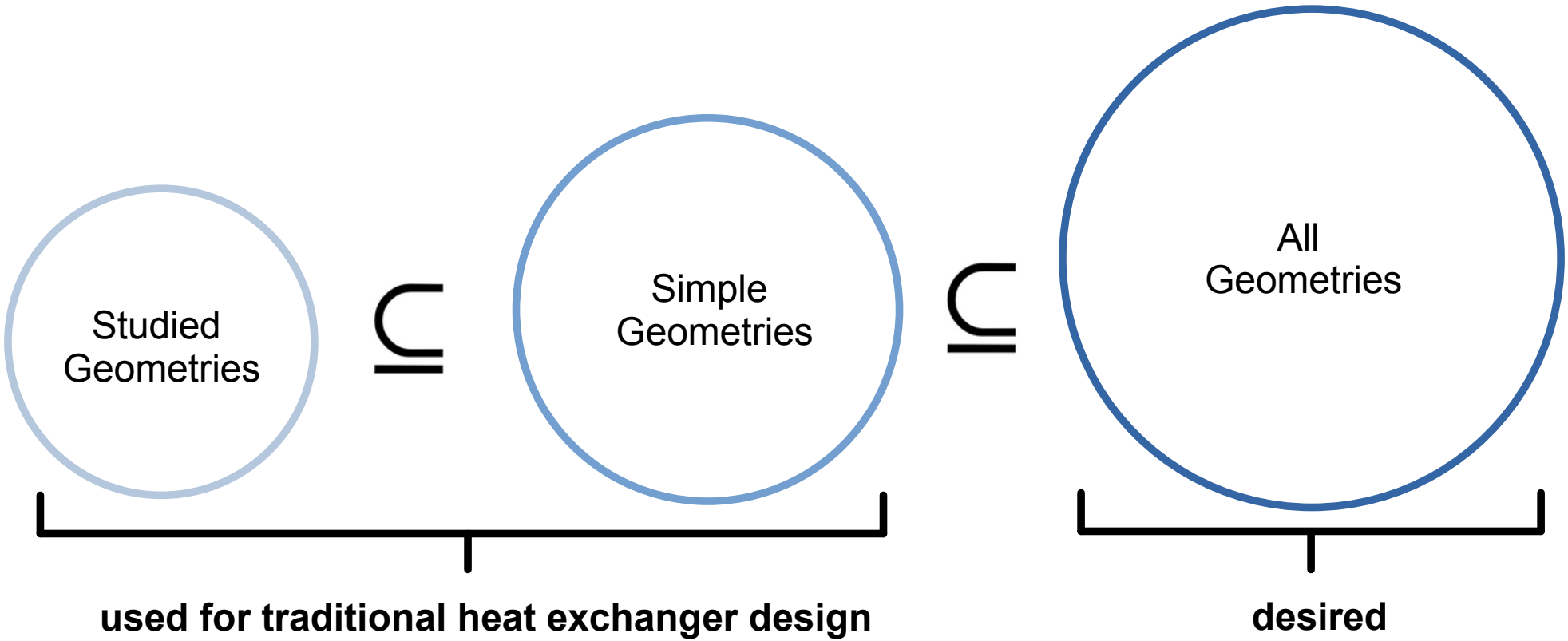
X-57



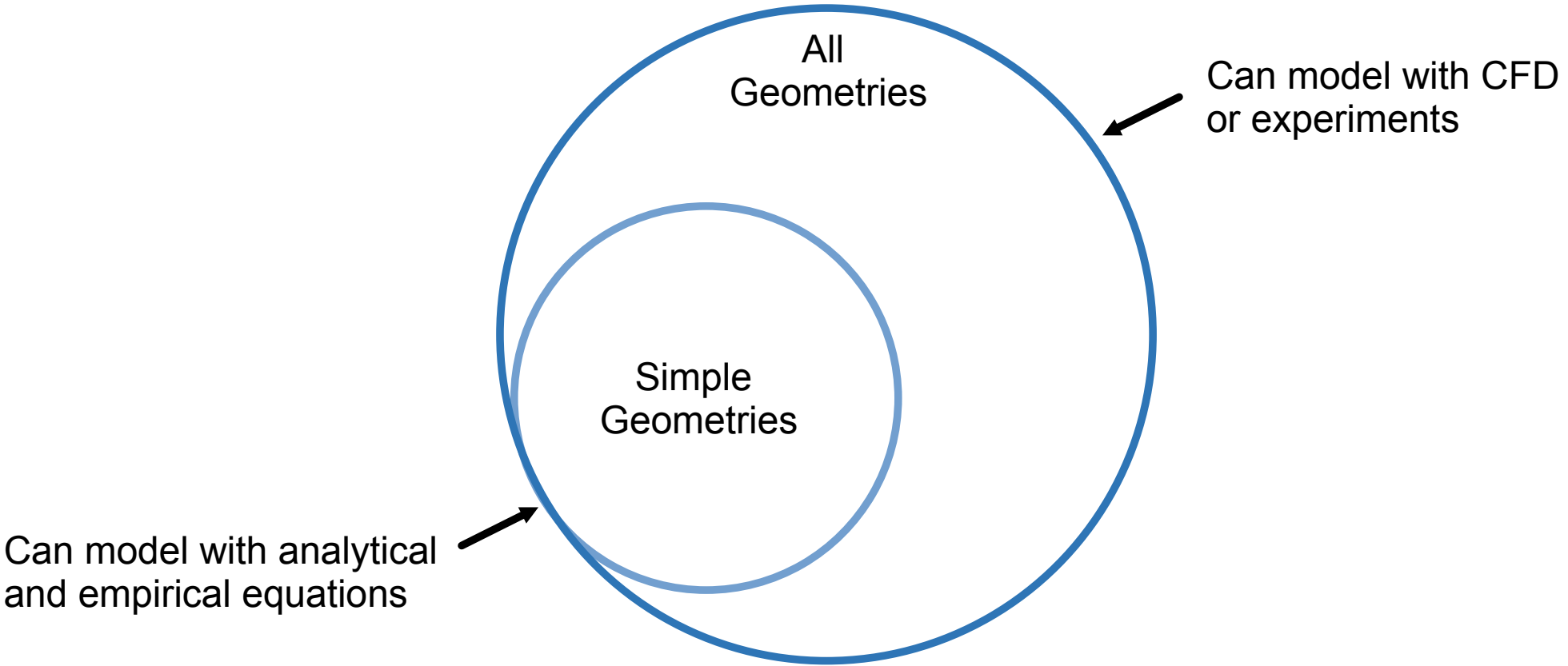
Spirit of Innovation



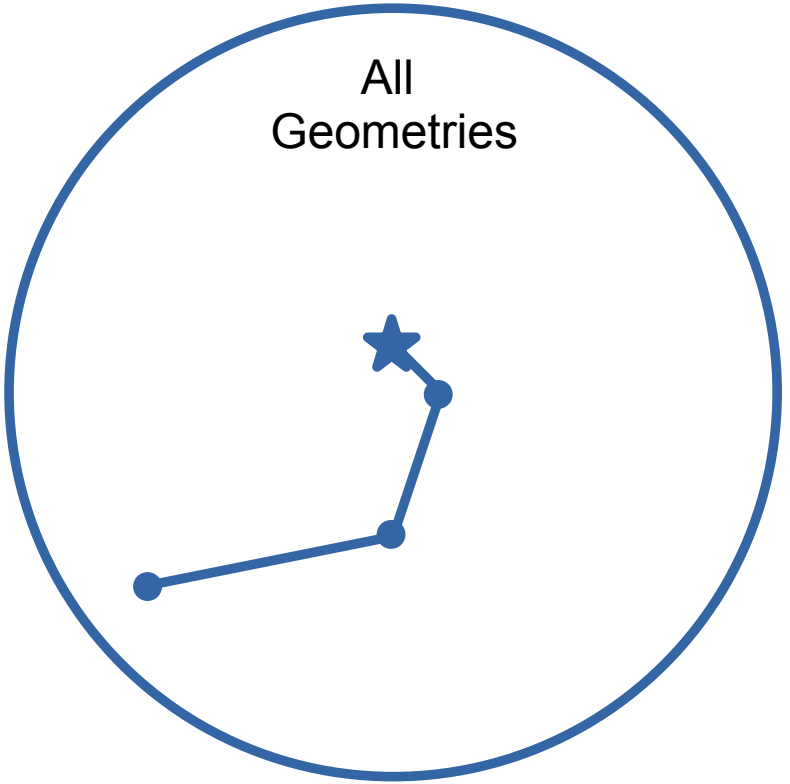
Traditional design process limited to simple and previously studied geometries



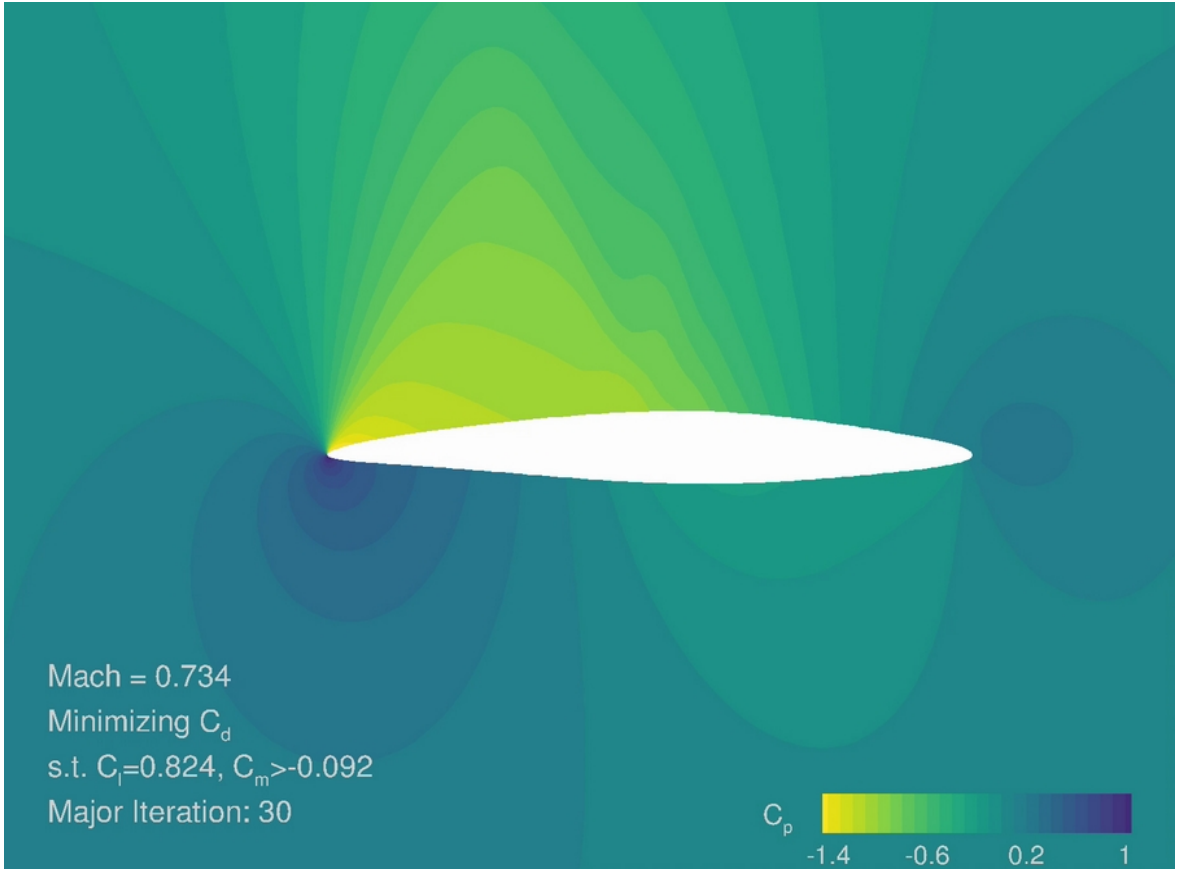
CFD has the generality required to evaluate beyond simple designs.



We propose CFD-based shape optimization to search for heat exchanger designs in a broader design space

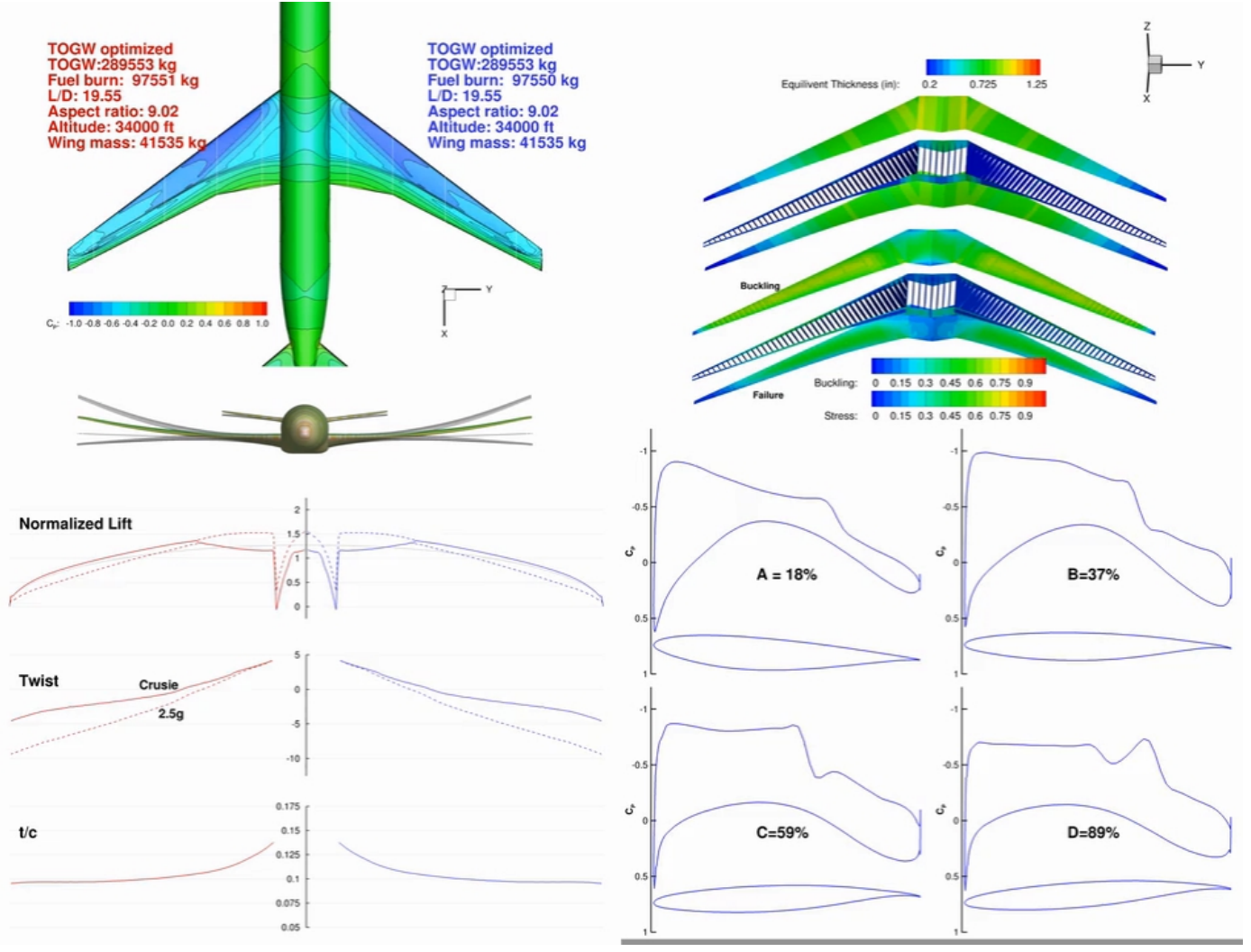


Shape optimization can be used to generate designs...



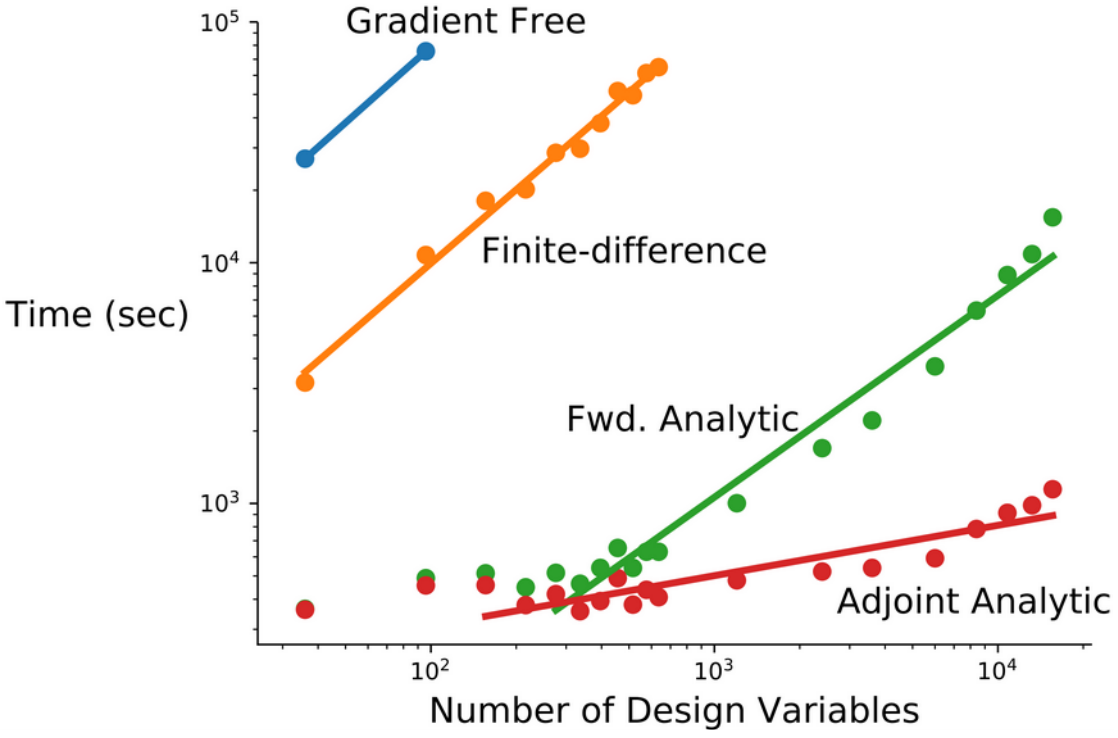
He, Li, Mader, Yildirim, and Martins
Robust aerodynamic shape optimization—from a circle to an airfoil, 2019.

…
or improve existing designs



Kenway and Martins.
Multipoint High-Fidelity Aerostructural Optimization of a Transport Aircraft Configuration, 2014

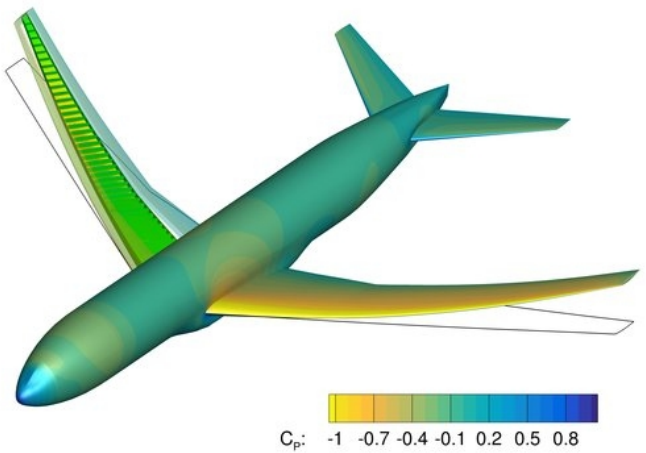
Gradient-based methods best suited for shape optimization



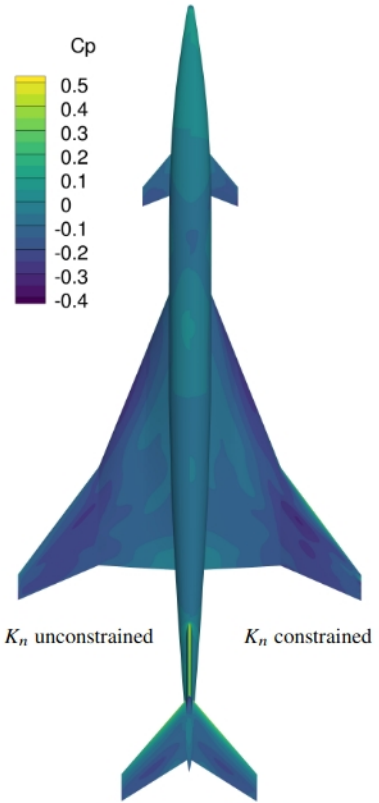
Gradient-based over 100x faster for aerodynamic shape optimization than gradient-free

Lyu, Xu, and Martins
Benchmarking Optimization Algorithms for Wing Aerodynamic Design Optimization, 2014

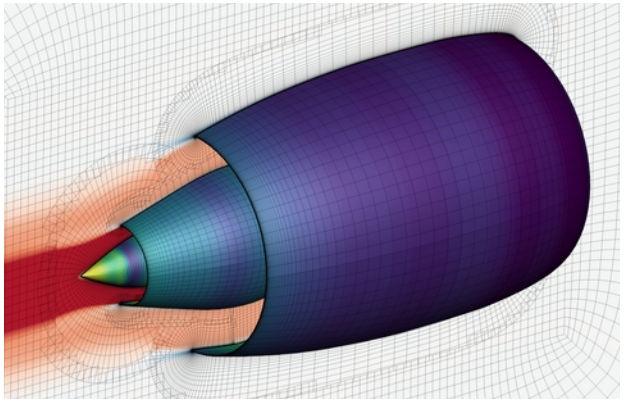
Adjoint-based optimization methods were developed for aerodynamic and aerostructural shape optimization problems by aerospace field



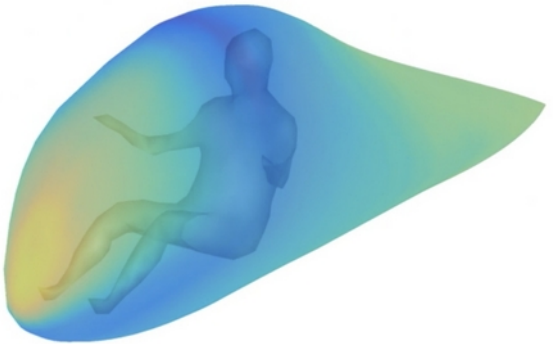
(Brooks et al. 2017)



(Seraj et al. 2022)

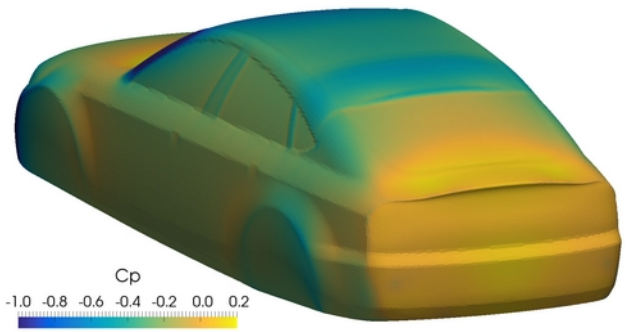


(Lamkin et al. 2022)

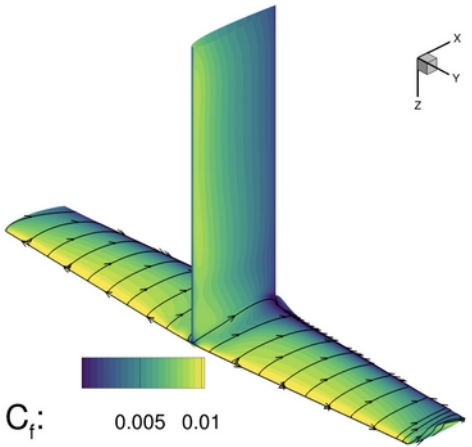


(Brelje et al. 2019)

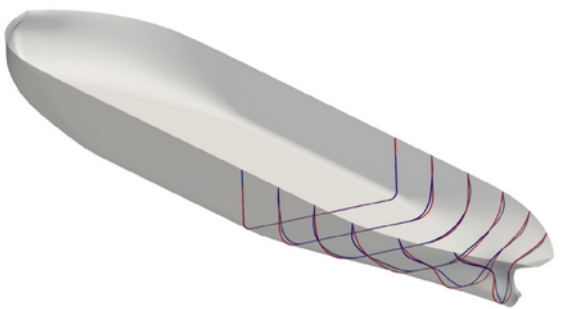
Adjoint-based shape optimization techniques have be applied to other fields



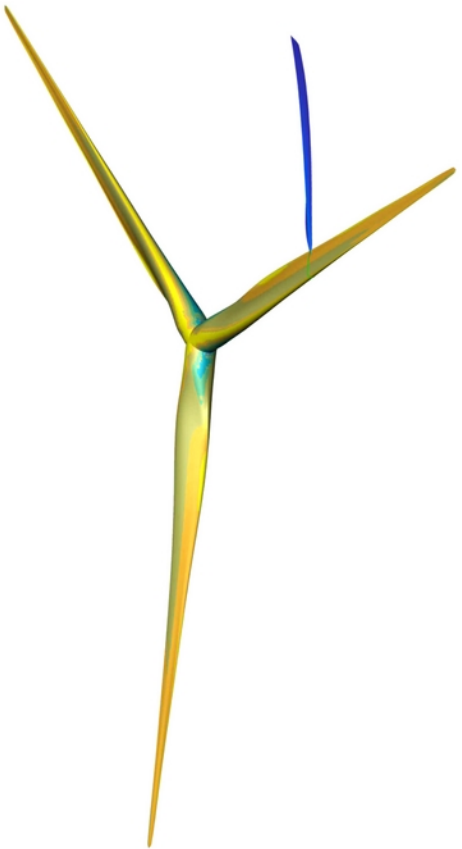
(He et al. 2017)



(Liao et al. 2020)

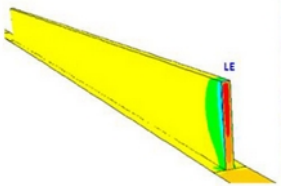


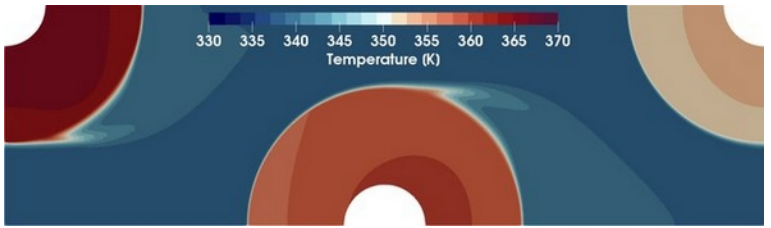
(He et al. 2019)



(Madsen et al. 2019)

Adjoint-based high-fidelity shape optimization has seen slow adoption for heat transfer applications





(Mousavi et al. 2010)

(Wang et al. 2015)

(Burghardt et al. 2022)

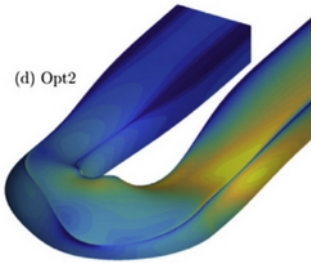
2010

2015

2020

(He et al. 2019)

(Economon et al. 2020)



To advance the field of adjoint-based heat exchanger design we aim to...

Aim 1. Apply gradient-based shape optimization to new heat exchanger geometries.

Aim 2. Use optimization as a tool to investigate heat exchanger design spaces

Aim 3. Develop tools for the optimization of heat exchangers

Road map

Open-source Framework for Heat Exchanger Optimization (Aim 3)

Optimization of a Plate-fin Heat Exchanger (Aim 1,2)

Optimization of a Surface Heat Exchanger (Aim 1,2)

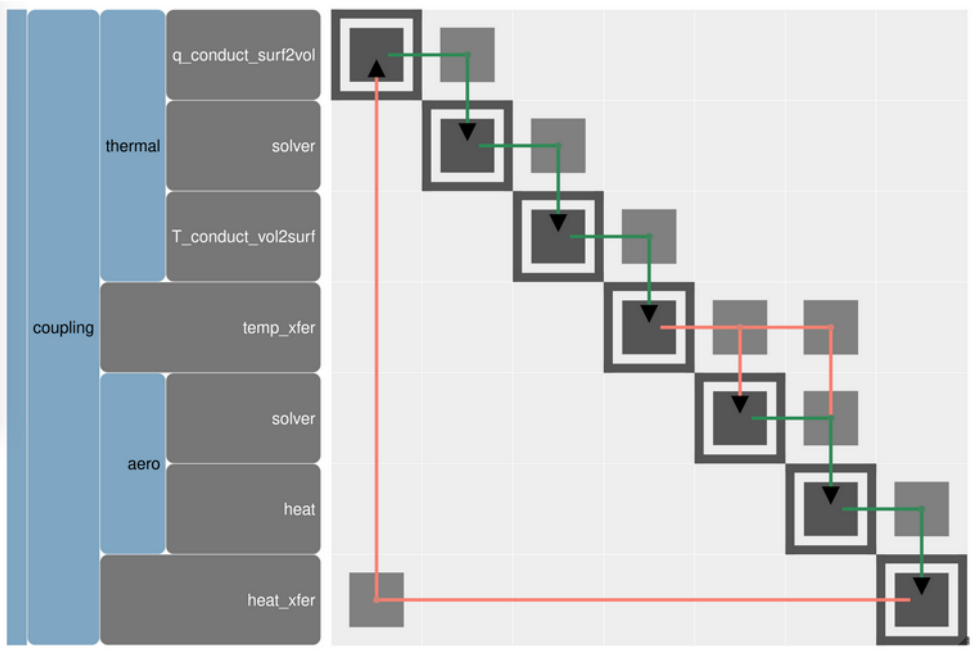
Road map

Open-source Framework for Heat Exchanger Optimization (Aim 3)

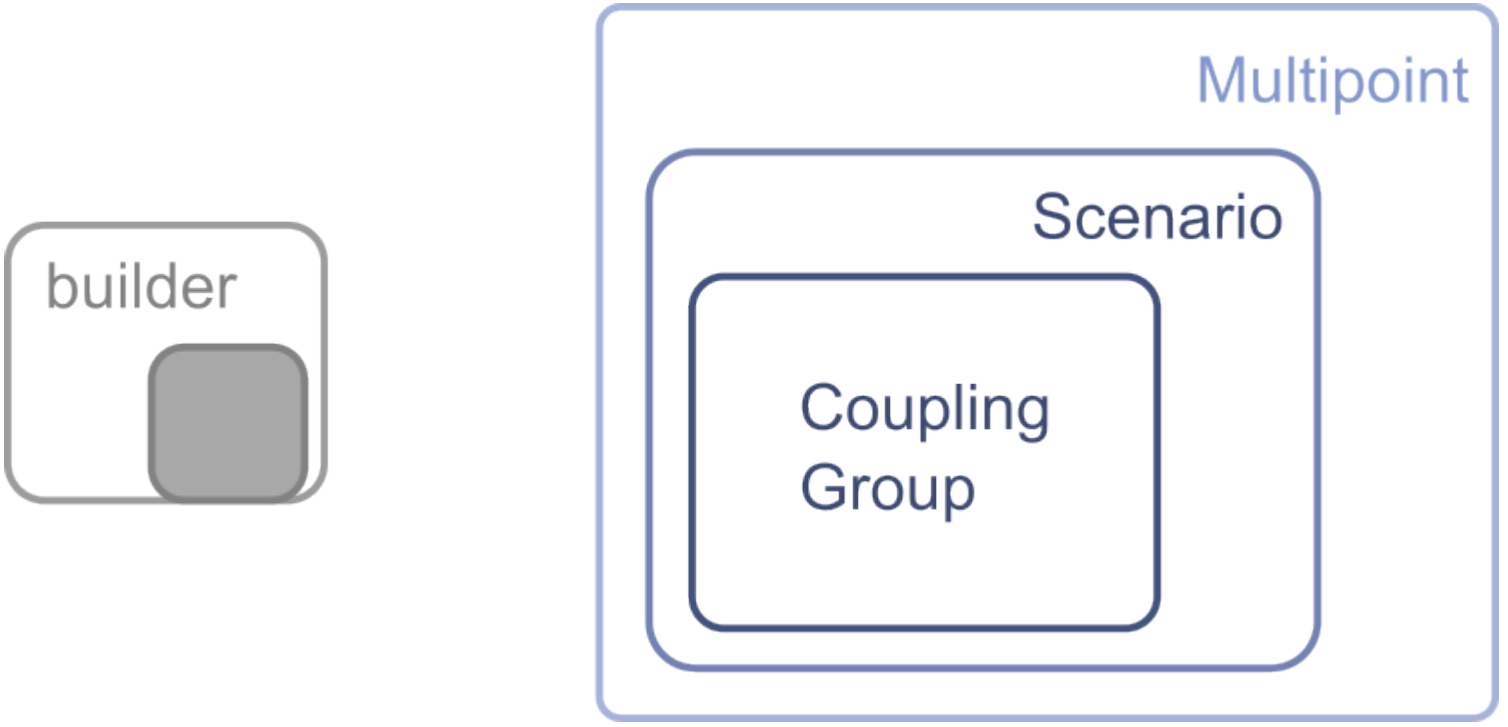
Optimization of a Plate-fin Heat Exchanger (Aim 1,2)

Optimization of a Surface Heat Exchanger (Aim 1,2)

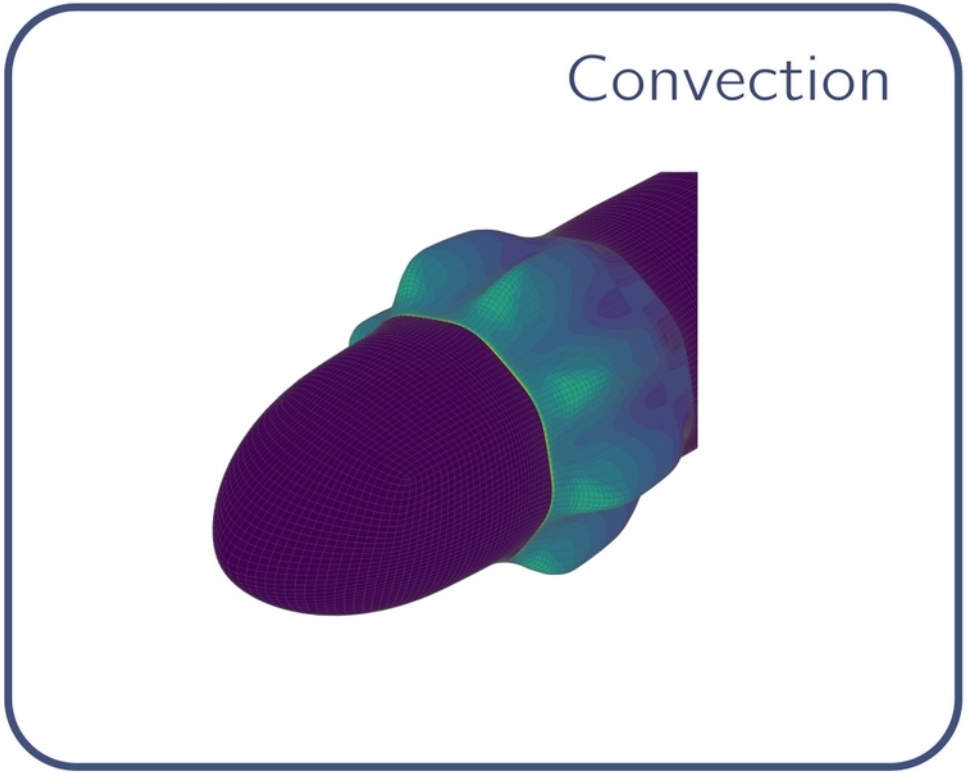
OpenMDAO is a framework for assembling models for analysis and optimization that supports gradients

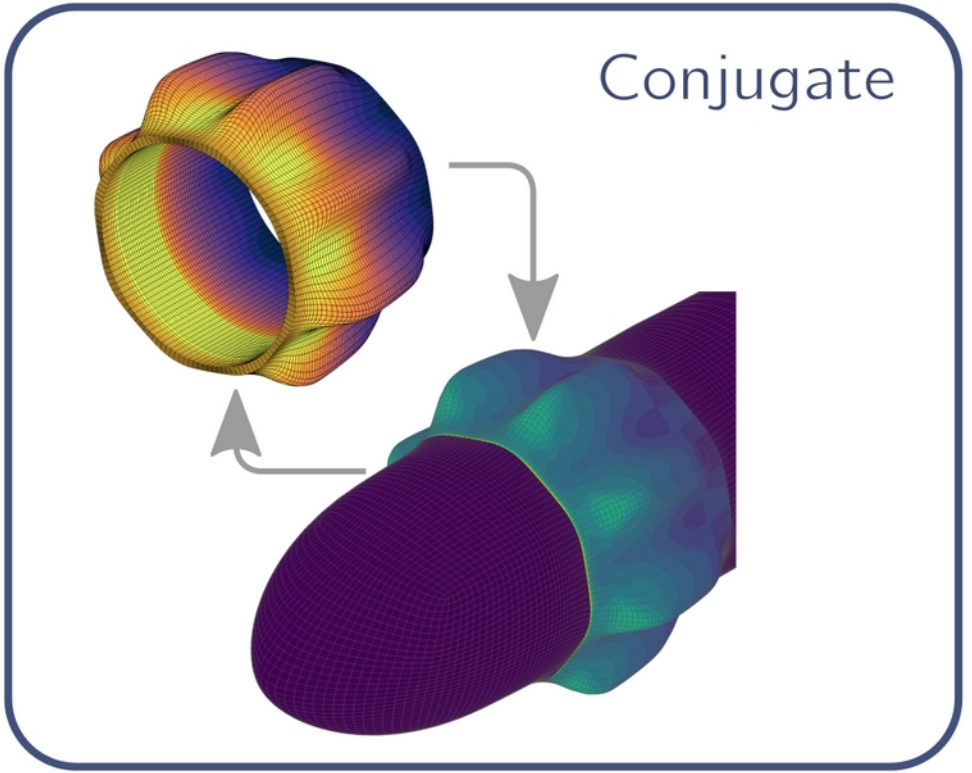


MPhys provides classes to build models in OpenMDAO

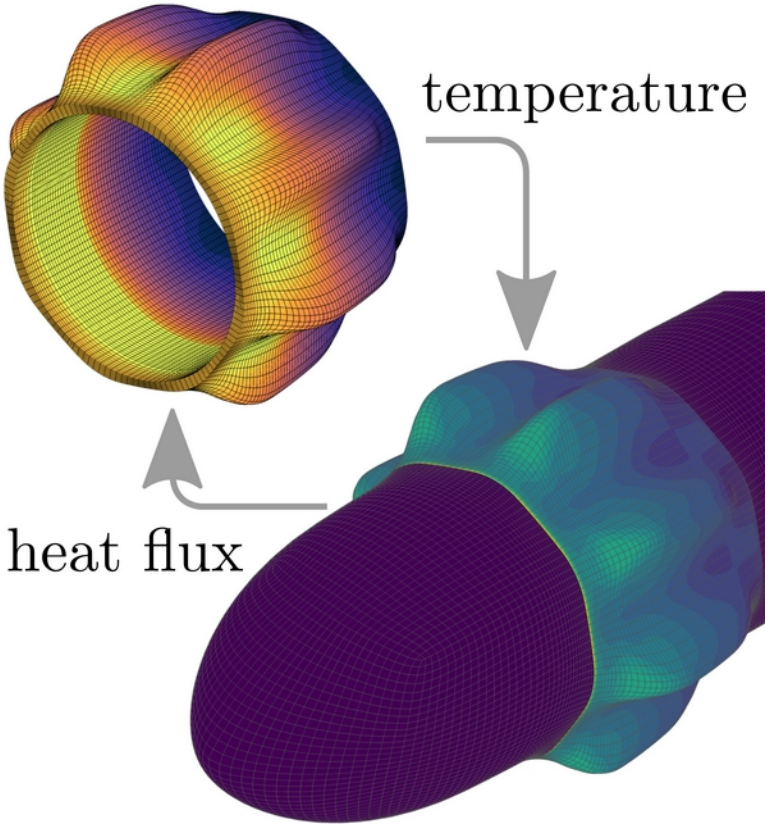


Adding convection and conjugate heat transfer coupling/scenario groups to MPhys

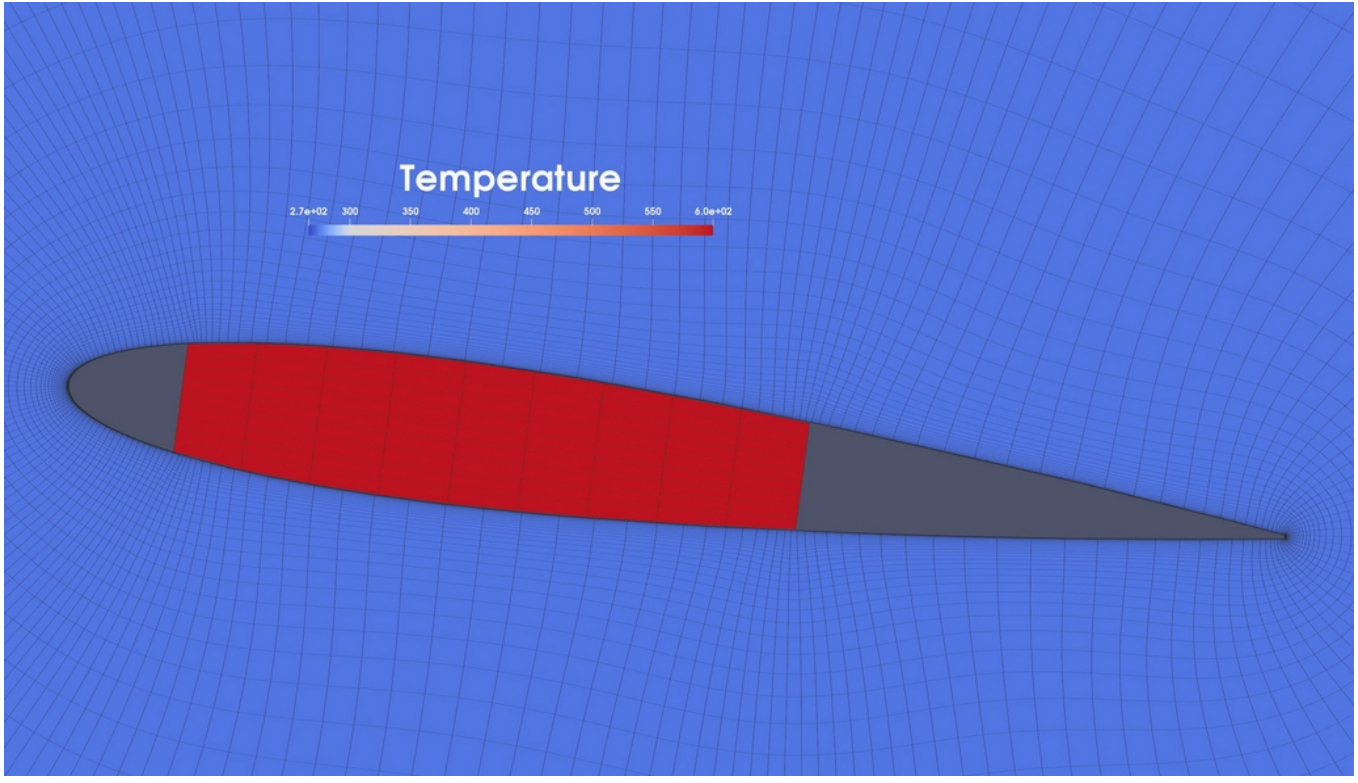




Conjugate coupling group is based on a “heatflux forward temperature back” approach



Applying an iterative non-linear solver to the group yields the solution to the conjugate problem



An iterative approach is also used to converge the coupled derivatives problems

$$\begin{bmatrix} \frac{\partial r_{\text{conv}}}{\partial u_{\text{conv}}} & \frac{\partial r_{\text{conv}}}{\partial u_{\text{cond}}} \\ \frac{\partial r_{\text{cond}}}{\partial u_{\text{conv}}} & \frac{\partial r_{\text{cond}}}{\partial u_{\text{cond}}} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} \psi_{\text{conv}} \\ \psi_{\text{cond}} \end{bmatrix} = -\begin{bmatrix} \frac{\partial \dot{Q}_{\text{total}}}{\partial u_{\text{conv}}} \\ \frac{\partial \dot{Q}_{\text{total}}}{\partial u_{\text{cond}}} \end{bmatrix}$$

Development of tools for heat exchanger optimization (Aim 3)

MPhys provides an open source implementation of adjoint based shape optimization for the optimization of heat exchangers.

Road map

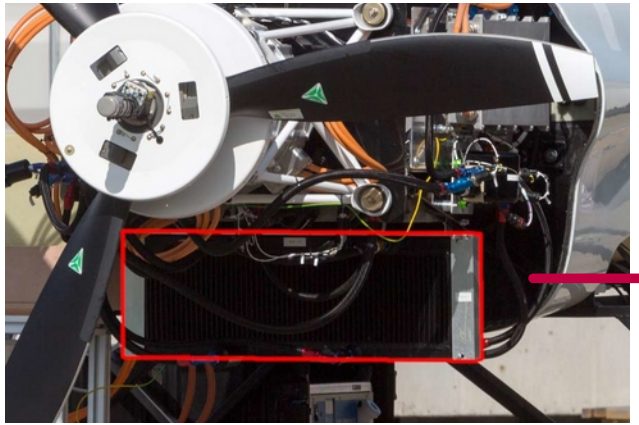
Open-source Framework for Heat Exchanger Optimization (Aim 3)

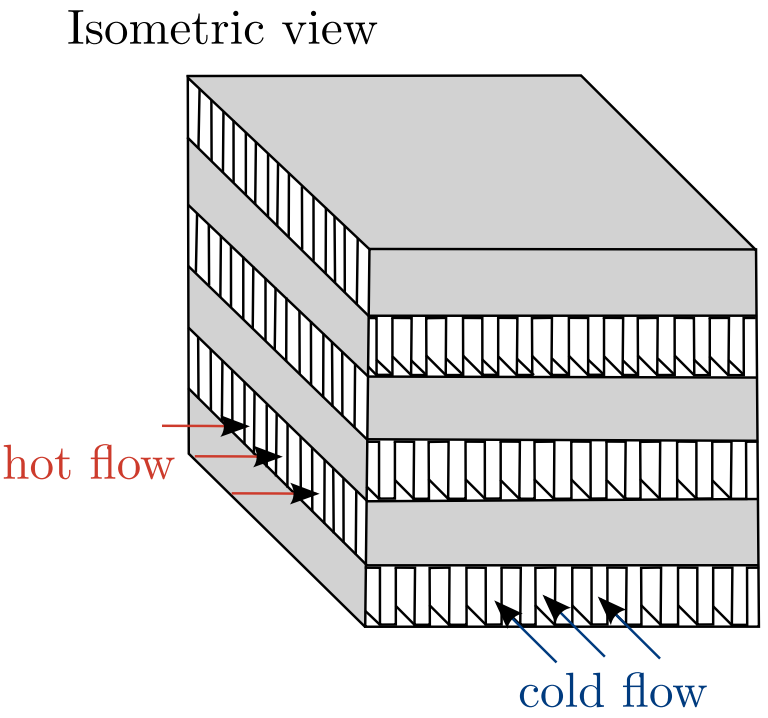
Optimization of a Plate-fin Heat Exchanger (Aim 1,2)

Optimization of a Surface Heat Exchanger (Aim 1,2)

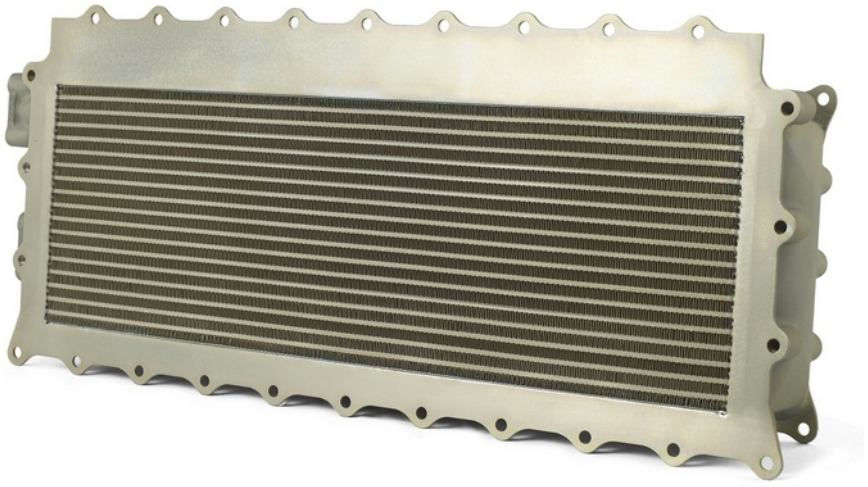
Plate-fin heat exchangers are common in aerospace

Spirit of Innovation

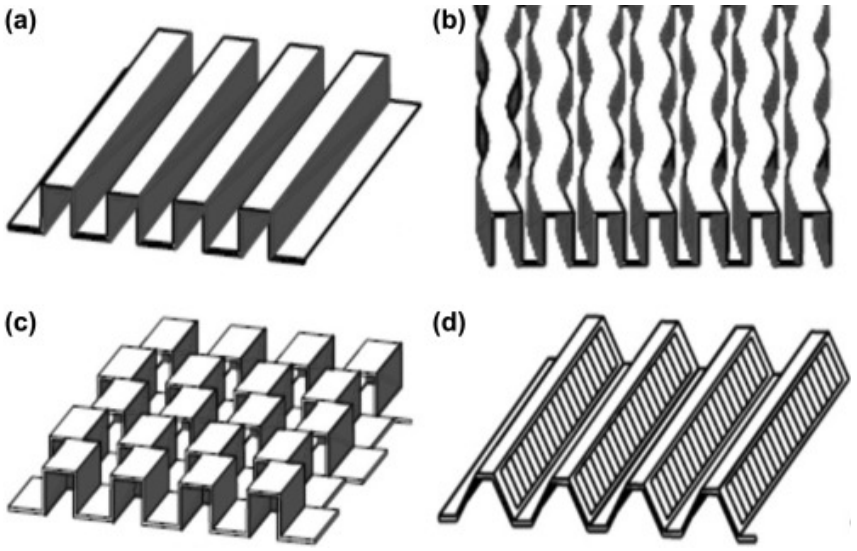




Fins can have different geometries



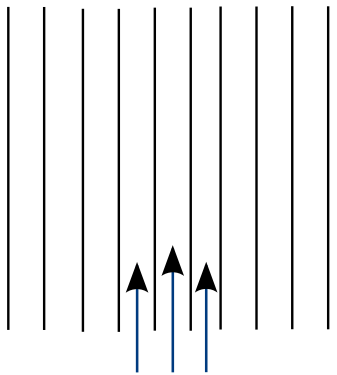
MEGGITT



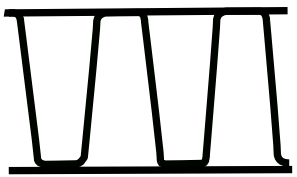
Sundén, B., and Fu, J., "**Aerospace Heat Exchangers**"

Baseline design has 15 layers and 55 plain fin channels

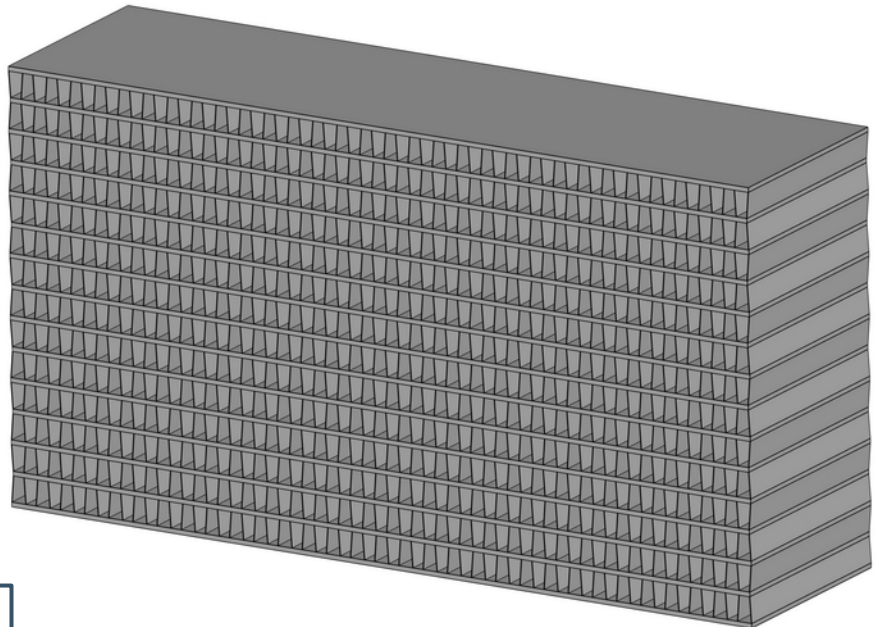
layer top view



cross section

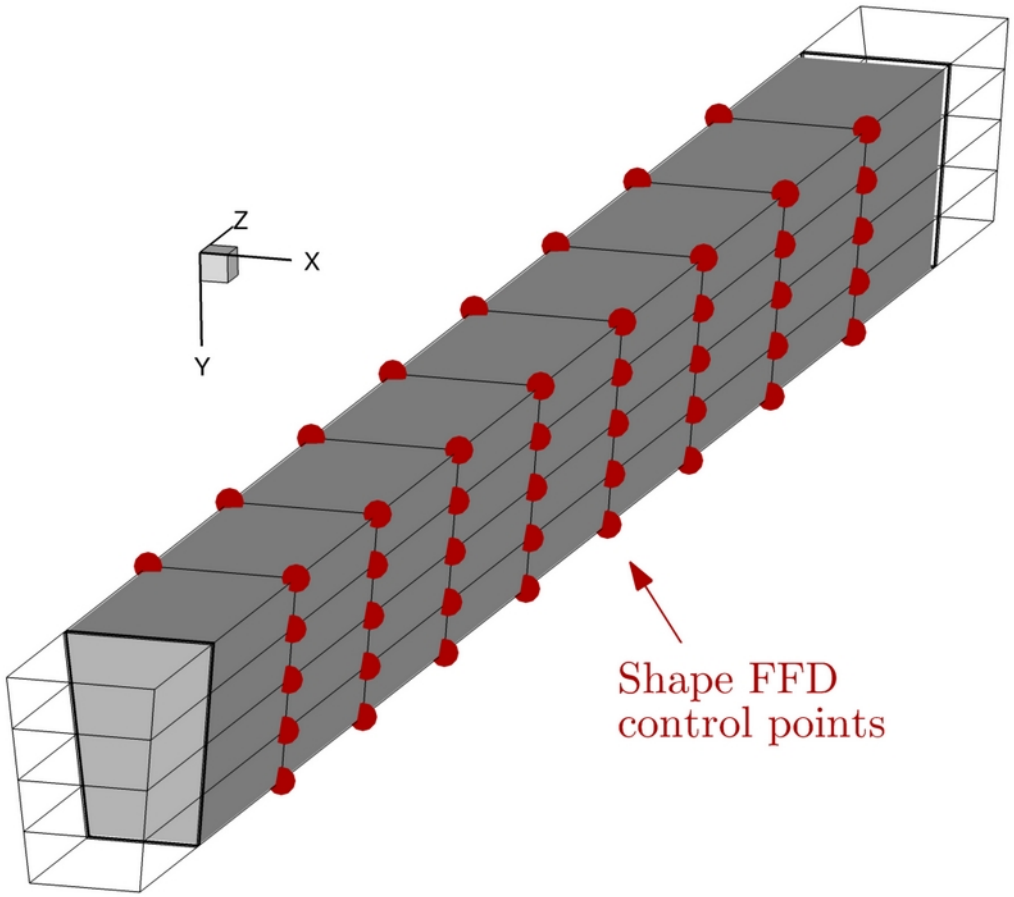


baseline design

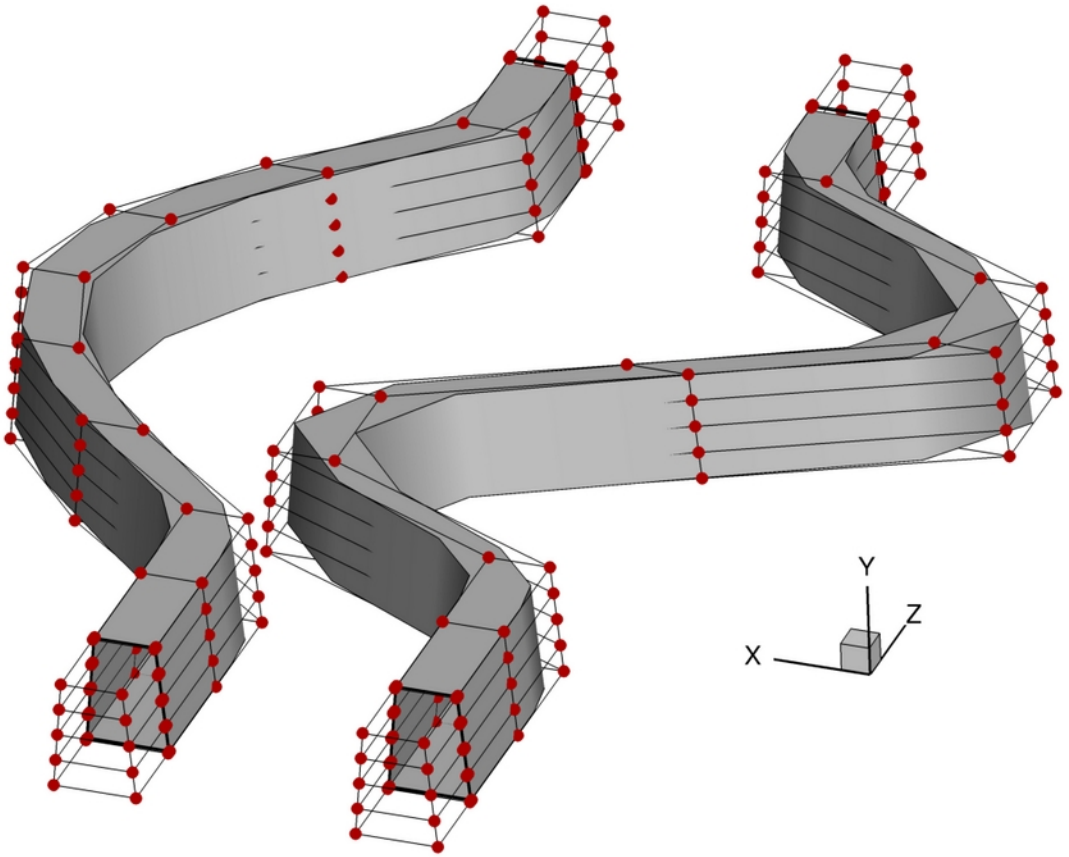


Geometry 2.0 of “Compact Heat Exchangers” by Kays and London

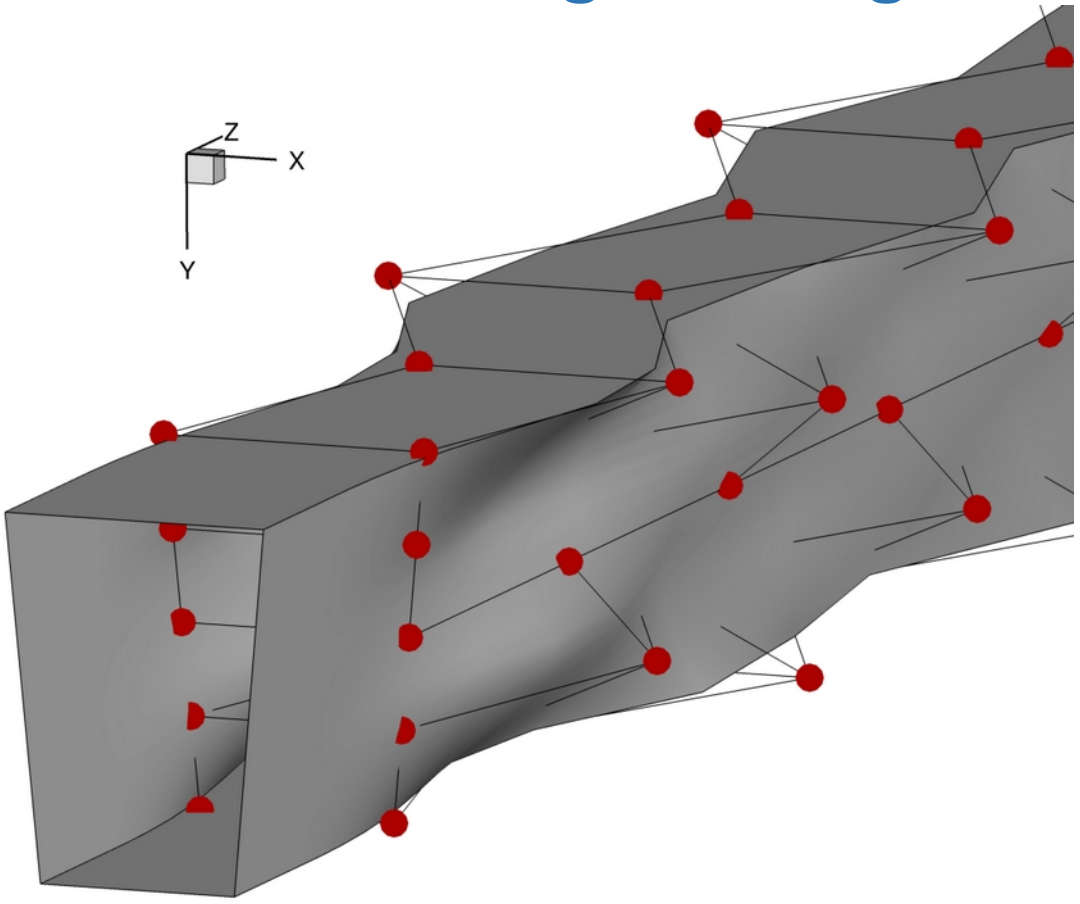
pyGeo deforms mesh according to design variables



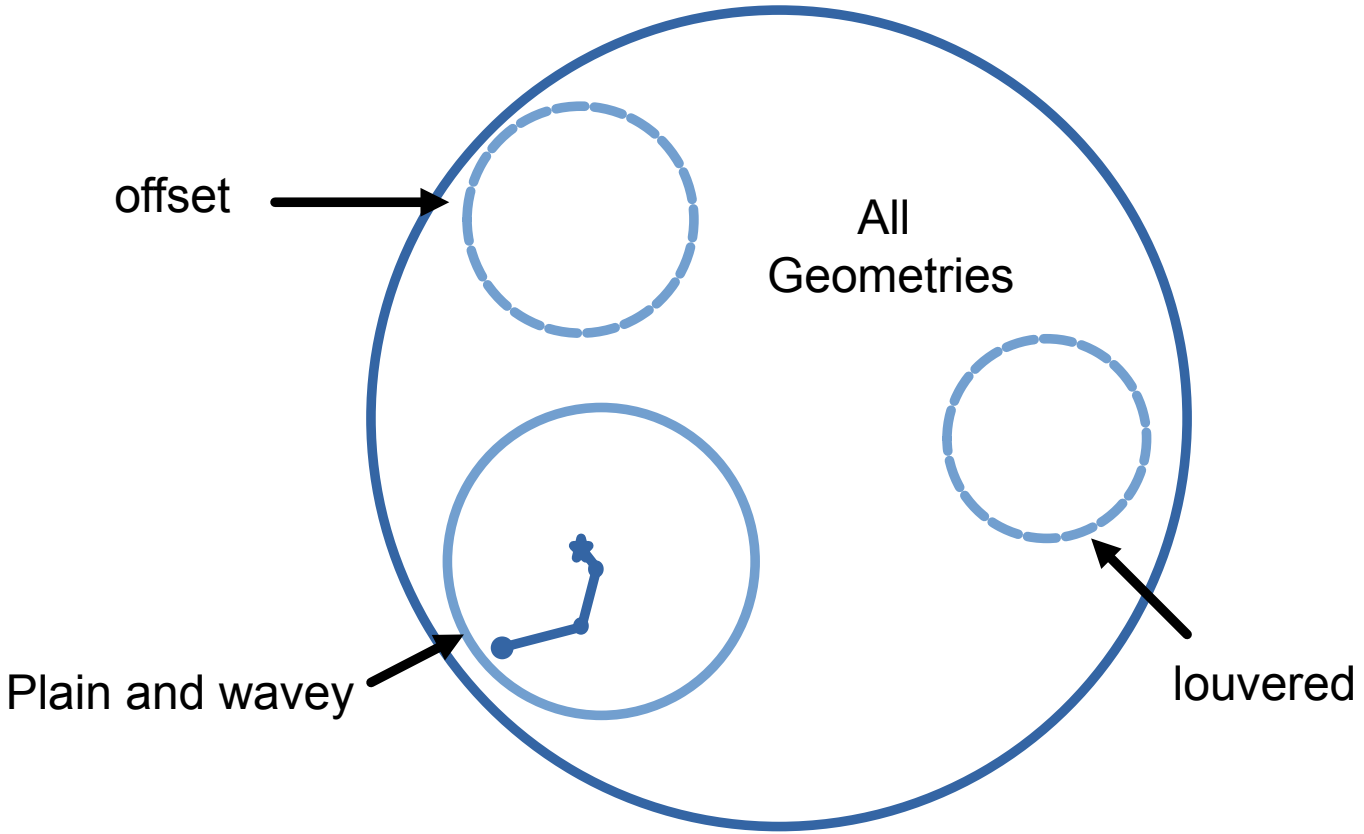
pyGeo deforms mesh according to design variables



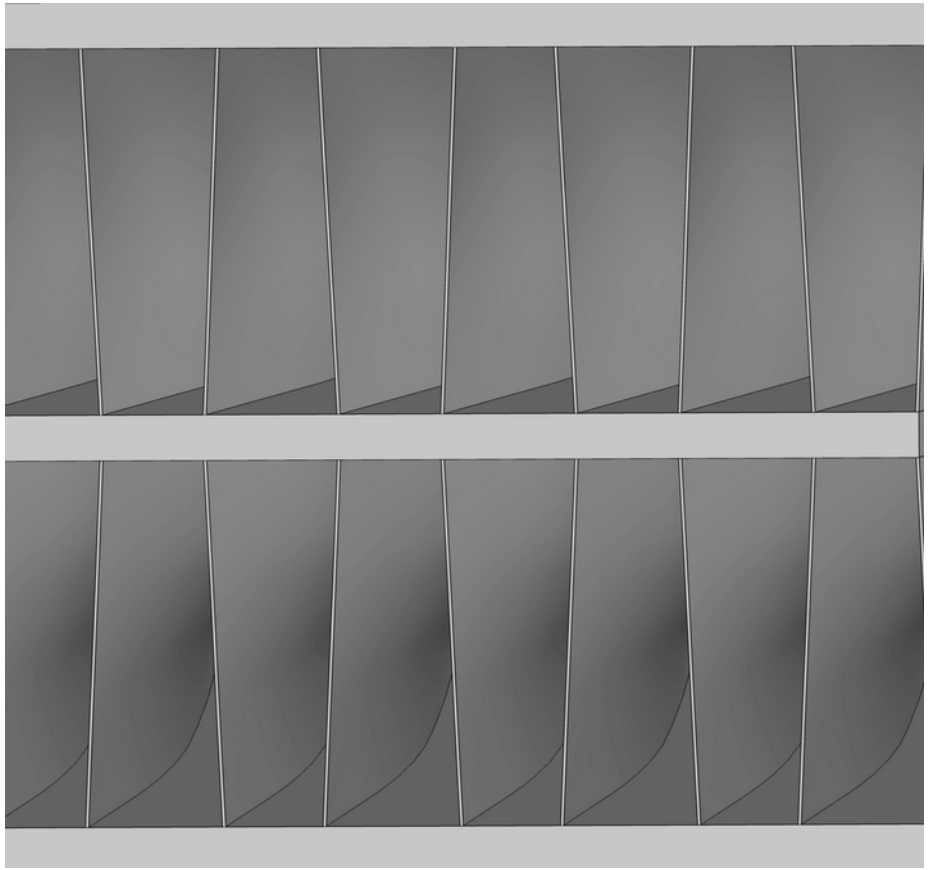
pyGeo deforms mesh according to design variables



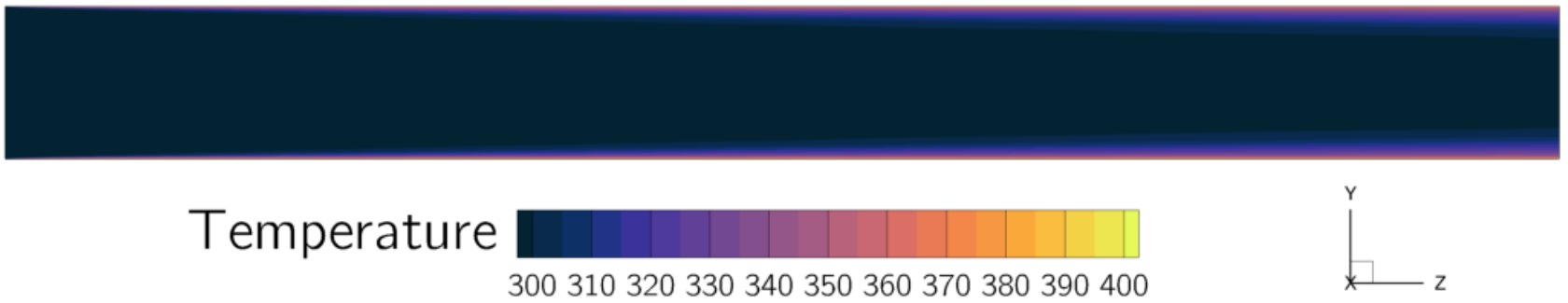
Parameterization can not add holes to create an offset fin from a plain initial design



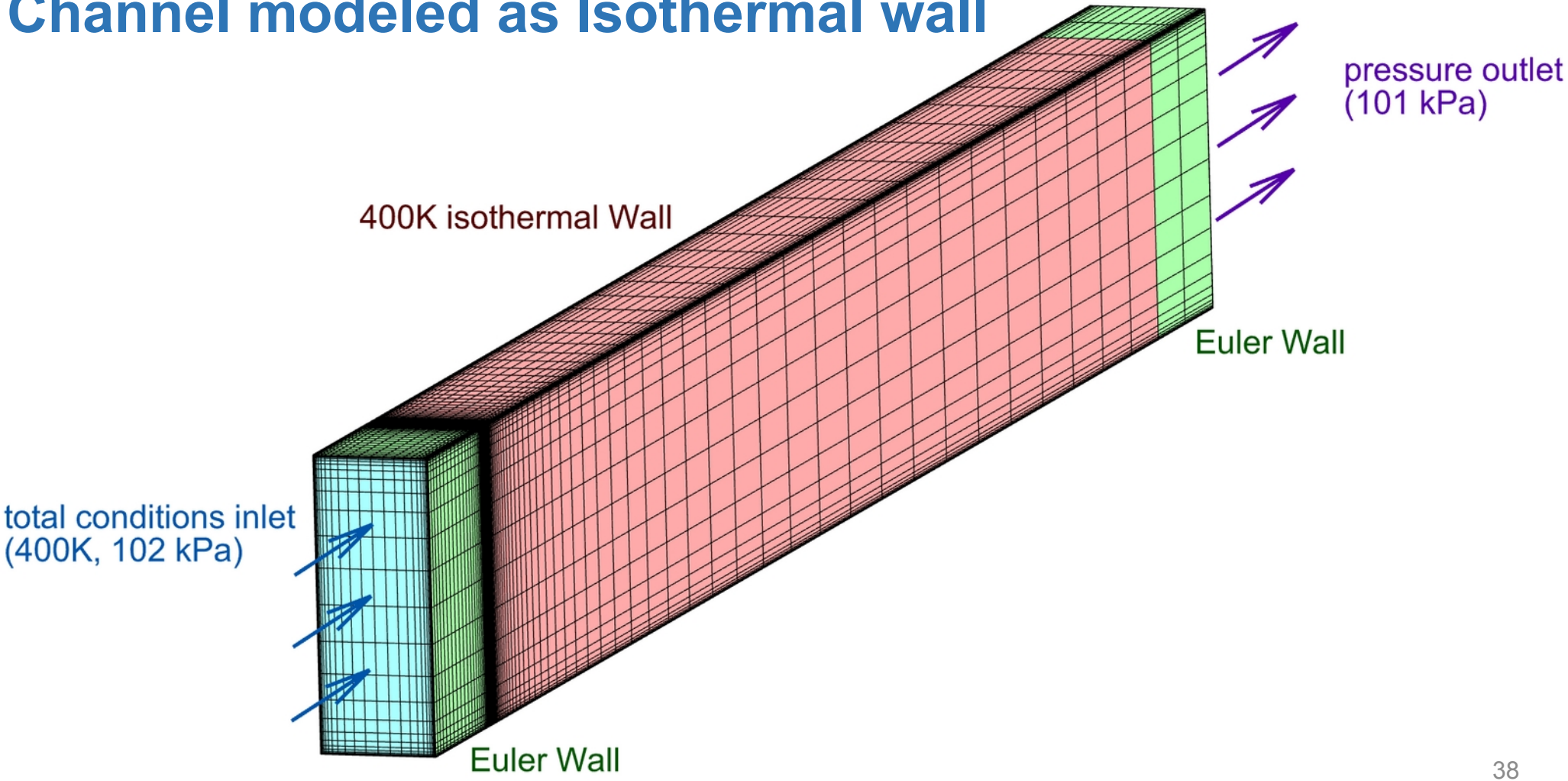
Shape deformations constrained to ensure the channel can be patterned to form layers



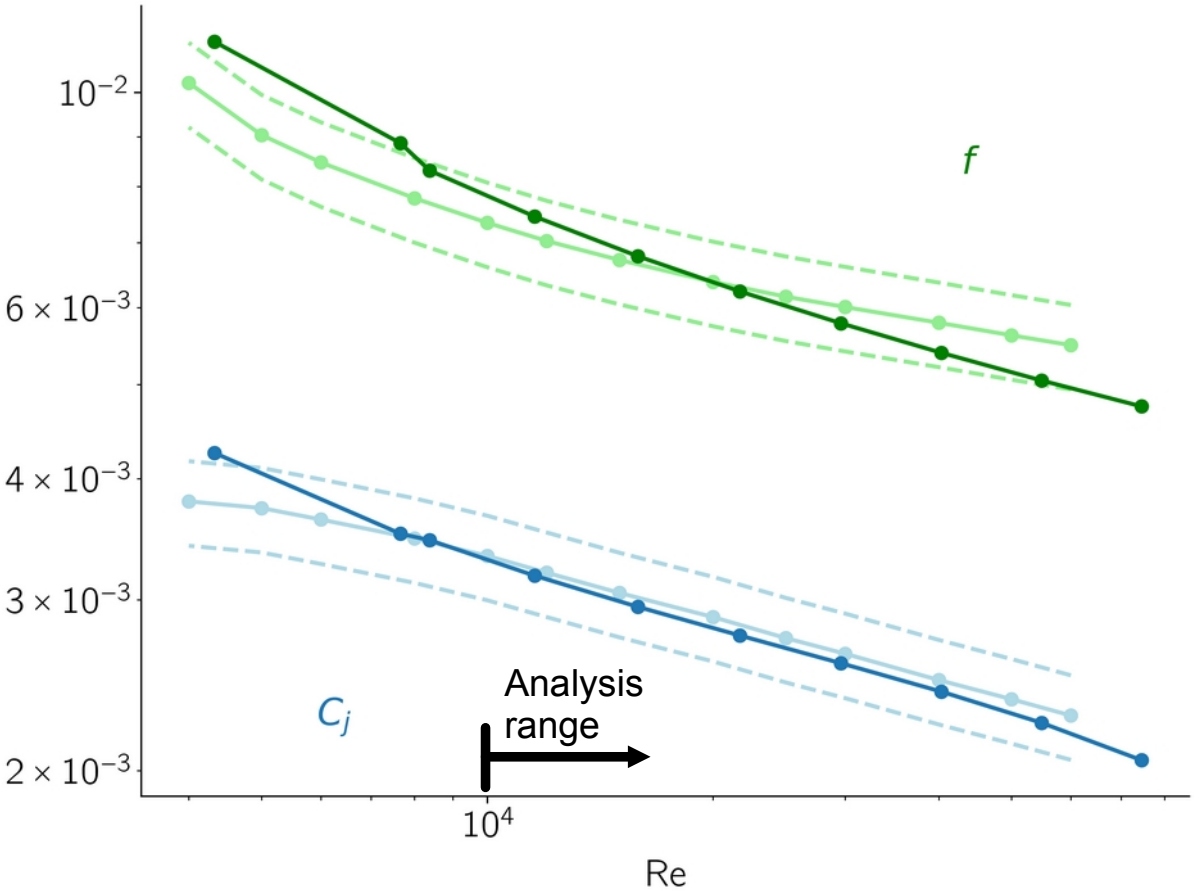
ADflow solves RANS equations for convective heat flux and drag



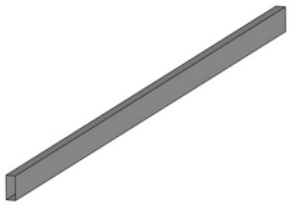
Channel modeled as Isothermal wall



Colburn factor and friction factors agree withing 10% for the range of Reynolds numbers used

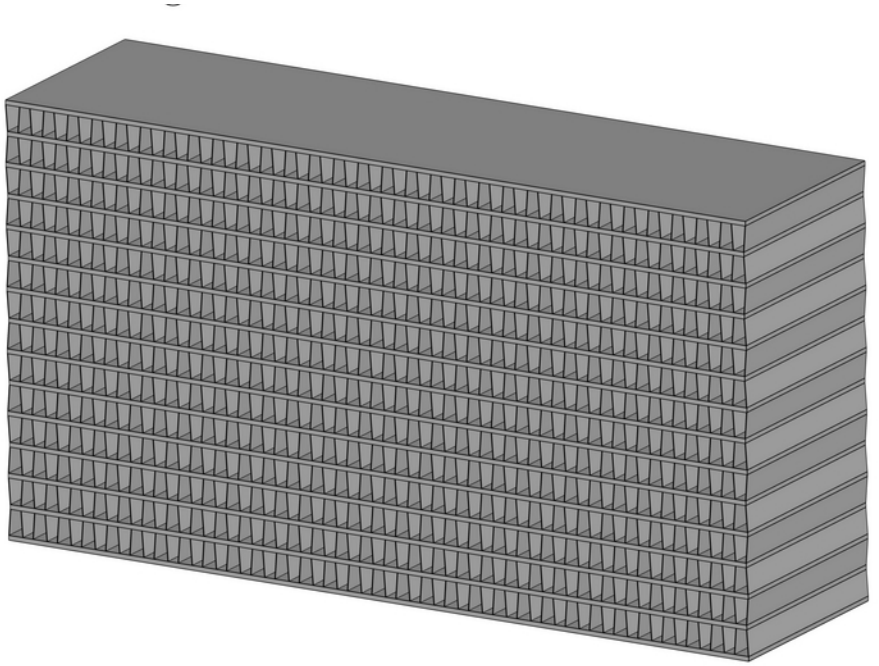


Channel properties scaled by number of channels and layers to find heat exchanger properties



Q, Drag, Mass

$N_{channels}$ X N_{layers}



Q_{Hx}, $Drag_{Hx}$, $Mass_{Hx}$

Drag and mass used as objective functions

	Variable	Description	Quantity
min	Drag	The total force in the z direction	1
or			
min	Mass	The total mass of the heat exchanger	1

Design variables control channel shape and total number of channels

	Variable	Description	Quantity
min	Drag	The total force in the z direction	1
or			
min	Mass	The total mass of the heat exchanger	1
w.r.t	s_{fins}	Position of FFD shape control points for each channel	70
	w_{channel}	Position of FFD wave control points for each channel	9
	L_{channel}	The length the channel	1
	W_{channel}	The width of the channel	1
	H_{channel}	The height of the channel	1
	$N_{\text{channel}}, N_{\text{layers}}$	Number of channels per layer and cold side layers	2

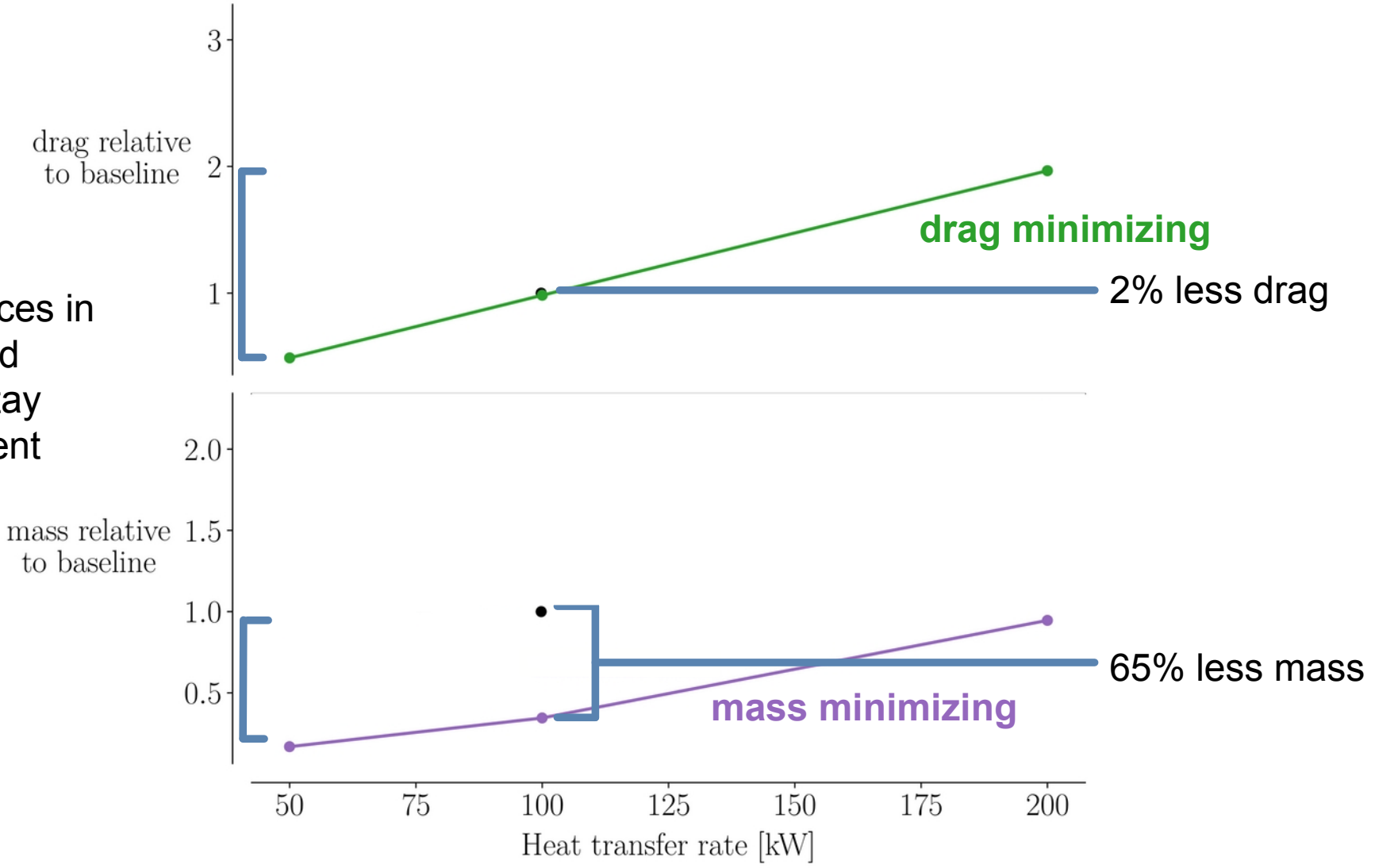
Heat load, shape, and compactness constraints applied

	Variable	Description	Quantity
min	Drag	The total force in the z direction	1
or			
min	Mass	The total mass of the heat exchanger	1
w.r.t	s_{fins}	Position of FFD shape control points for each channel	70
	w_{channel}	Position of FFD wave control points for each channel	9
	L_{channel}	The length the channel	1
	W_{channel}	The width of the channel	1
	H_{channel}	The height of the channel	1
	$N_{\text{channel}}, N_{\text{layers}}$	Number of channels per layer and cold side layers	2
s.t.	$\dot{Q} \geq \dot{Q}_{\text{max}}$	Total heat transfer rate greater than or equal to heat load	1
	$s_{T,i} = -s_{B,i}$	Changes to fin shape must be opposite on the top and bottom	70
	$H_{\text{total}} \leq H_{\text{total},0}$	The total height must be less than or equal to the initial	1
	$W_{\text{total}} \leq W_{\text{total},0}$	The total width must be less than or equal to the initial	1

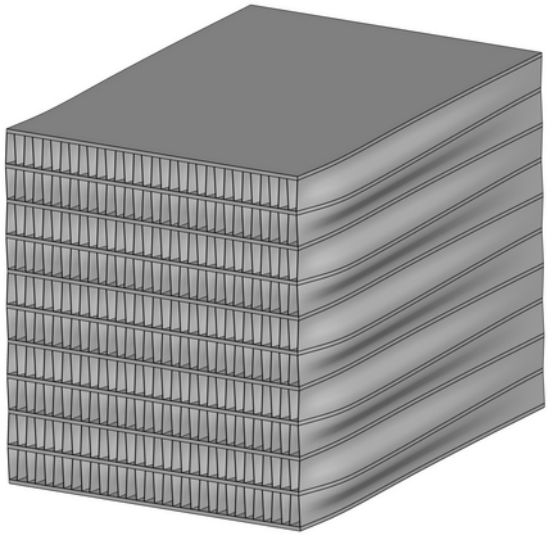
84 design variables and 73 constraints total

	Variable	Description	Quantity
min	Drag	The total force in the z direction	1
or			
min	Mass	The total mass of the heat exchanger	1
w.r.t	s_{fins}	Position of FFD shape control points for each channel	70
	w_{channel}	Position of FFD wave control points for each channel	9
	L_{channel}	The length the channel	1
	W_{channel}	The width of the channel	1
	H_{channel}	The height of the channel	1
	$N_{\text{channel}}, N_{\text{layers}}$	Number of channels per layer and cold side layers	2
s.t.	$\dot{Q} \geq \dot{Q}_{\text{max}}$	Total heat transfer rate greater than or equal to heat load	1
	$s_{T,i} = -s_{B,i}$	Changes to fin shape must be opposite on the top and bottom	70
	$H_{\text{total}} \leq H_{\text{total},0}$	The total height must be less than or equal to the initial	1
	$W_{\text{total}} \leq W_{\text{total},0}$	The total width must be less than or equal to the initial	1

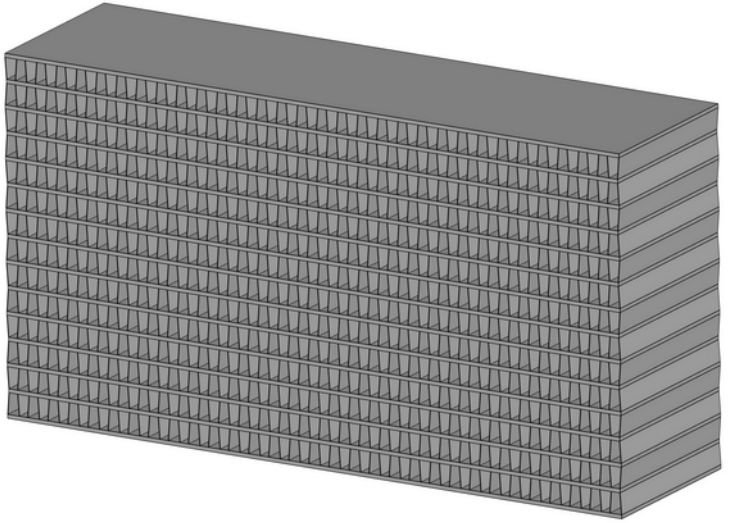
differences in drag and mass stay consistent



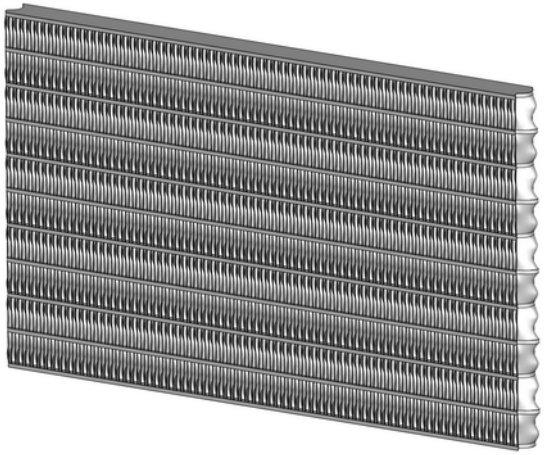
Optimized designs have fewer layers with taller channels



drag minimizing 100 kW

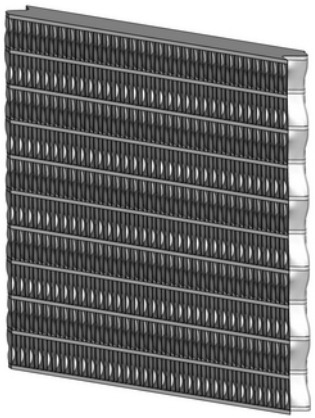


baseline (100 kW)

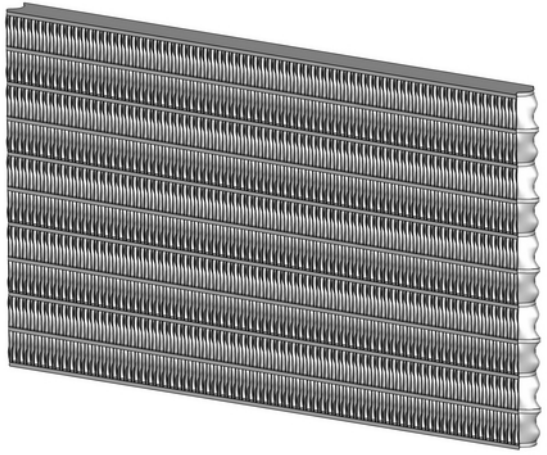


mass minimizing 100 kW

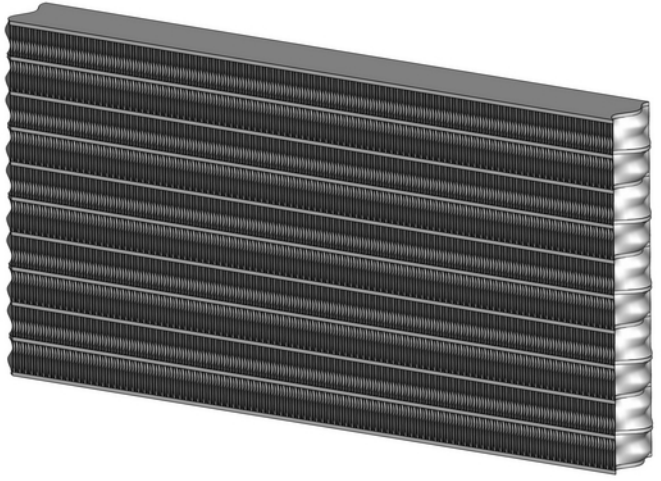
Mass minimizing designs are short with many channels



50 kW

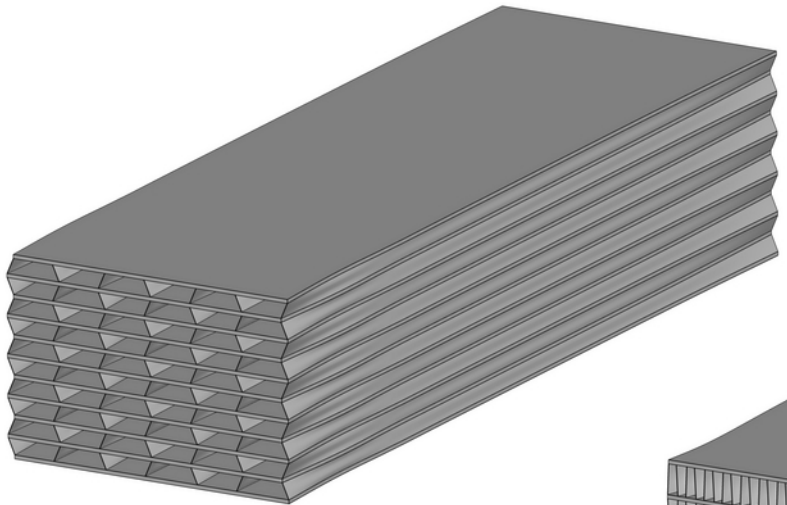


100 kW

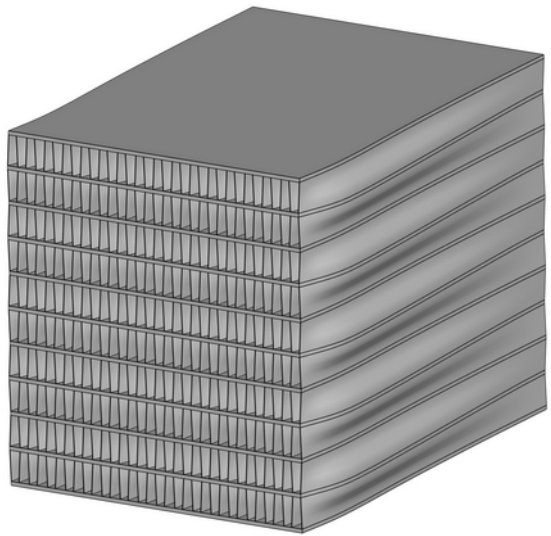


200 kW

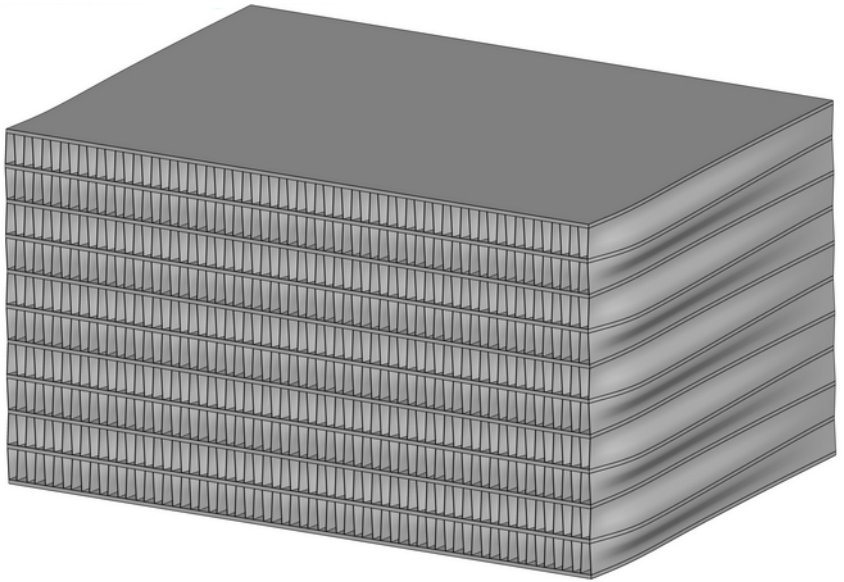
Drag minimizing designs are longer with fewer channels



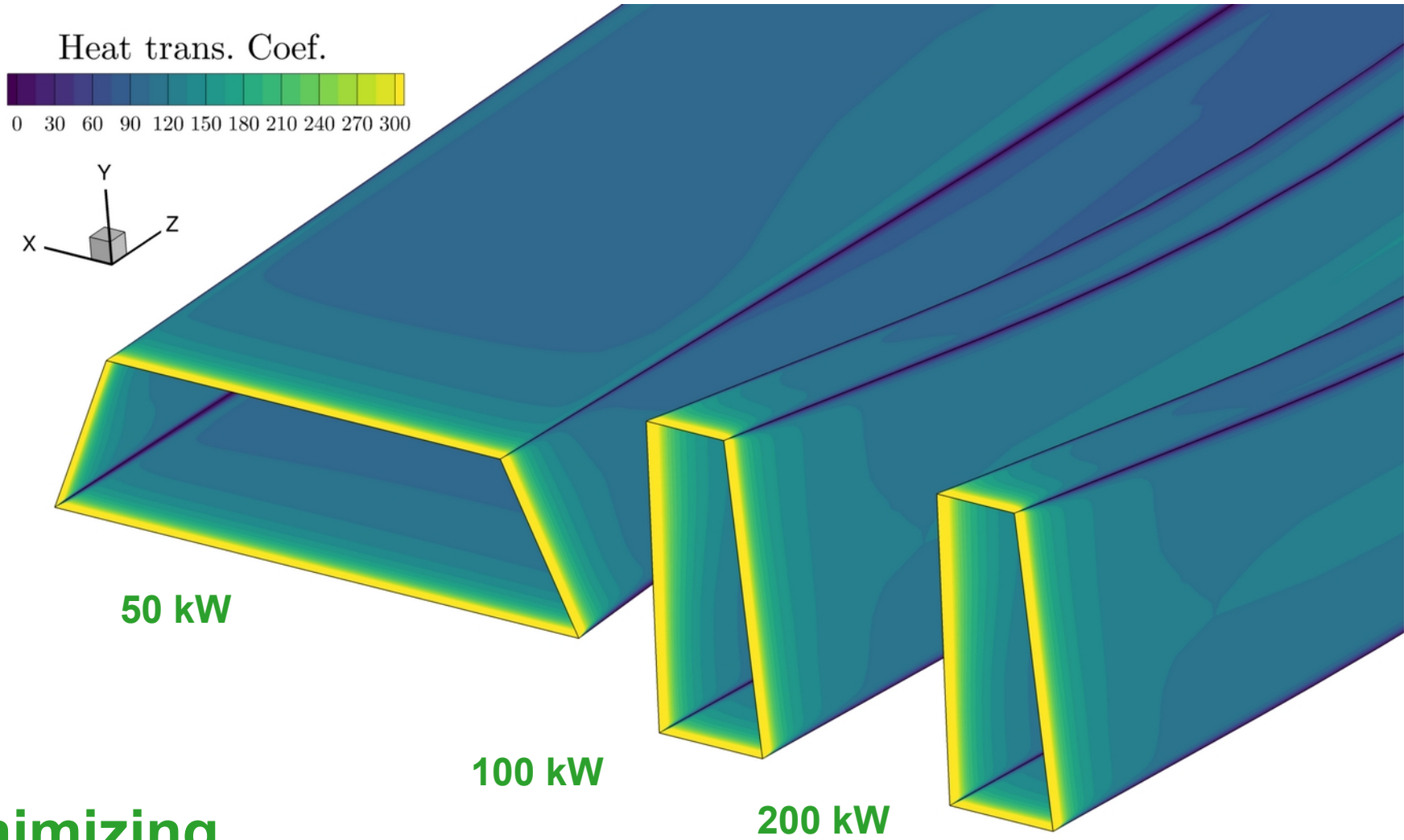
50 kW



100 kW

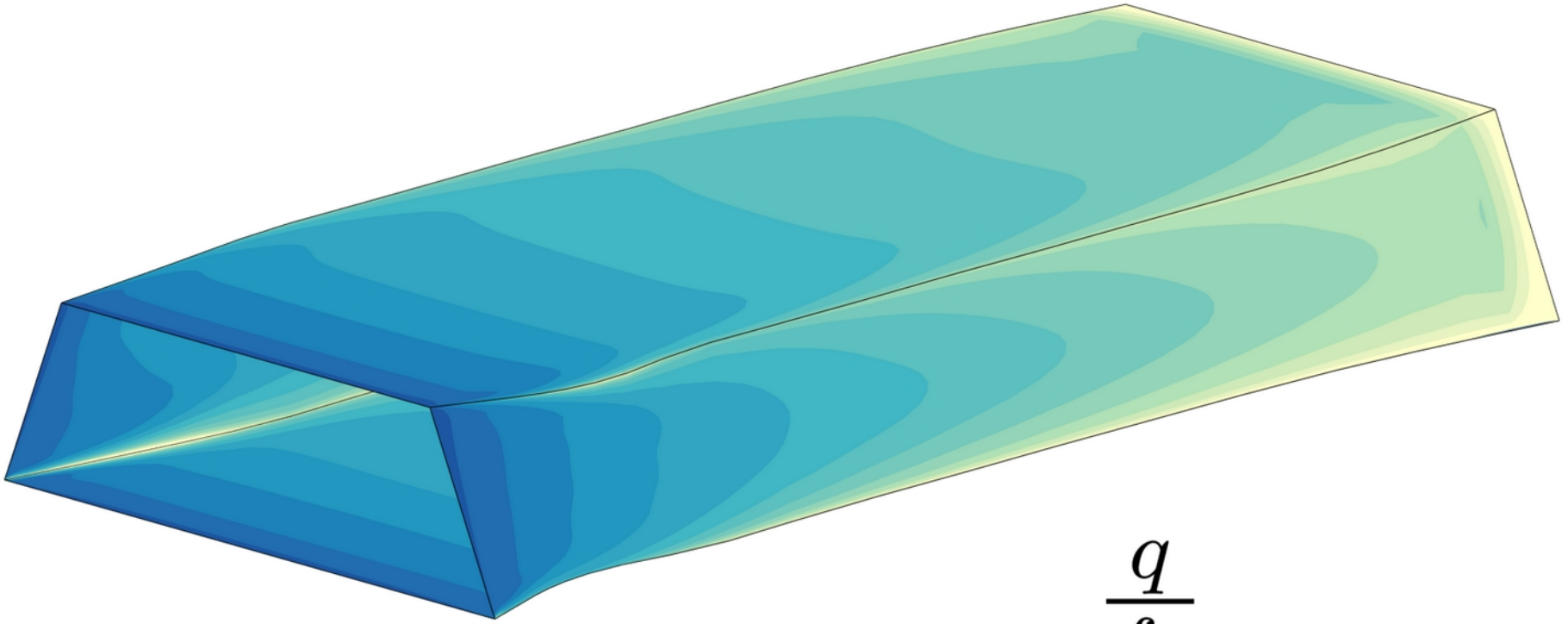


200 kW

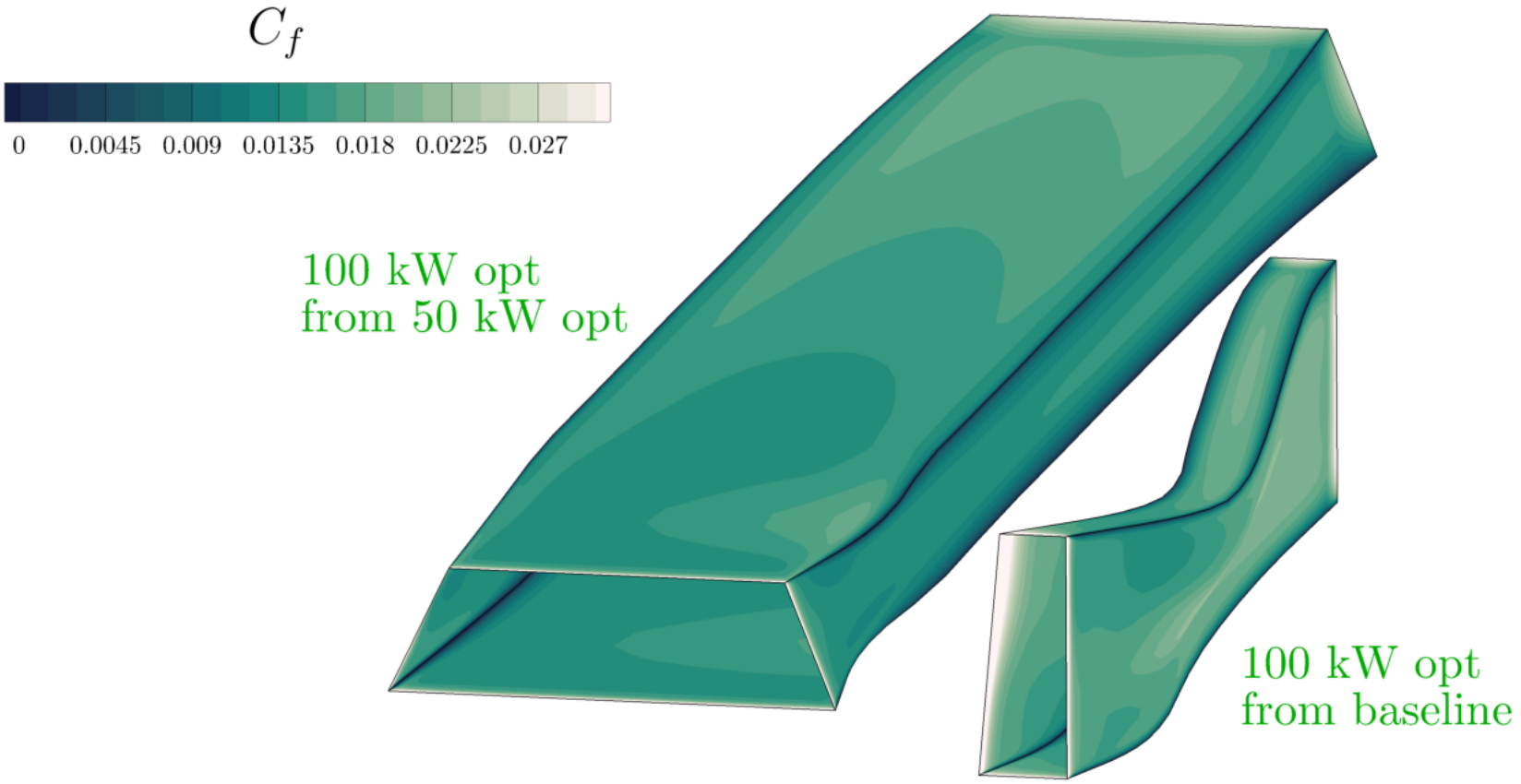


Drag minimizing channels are larger

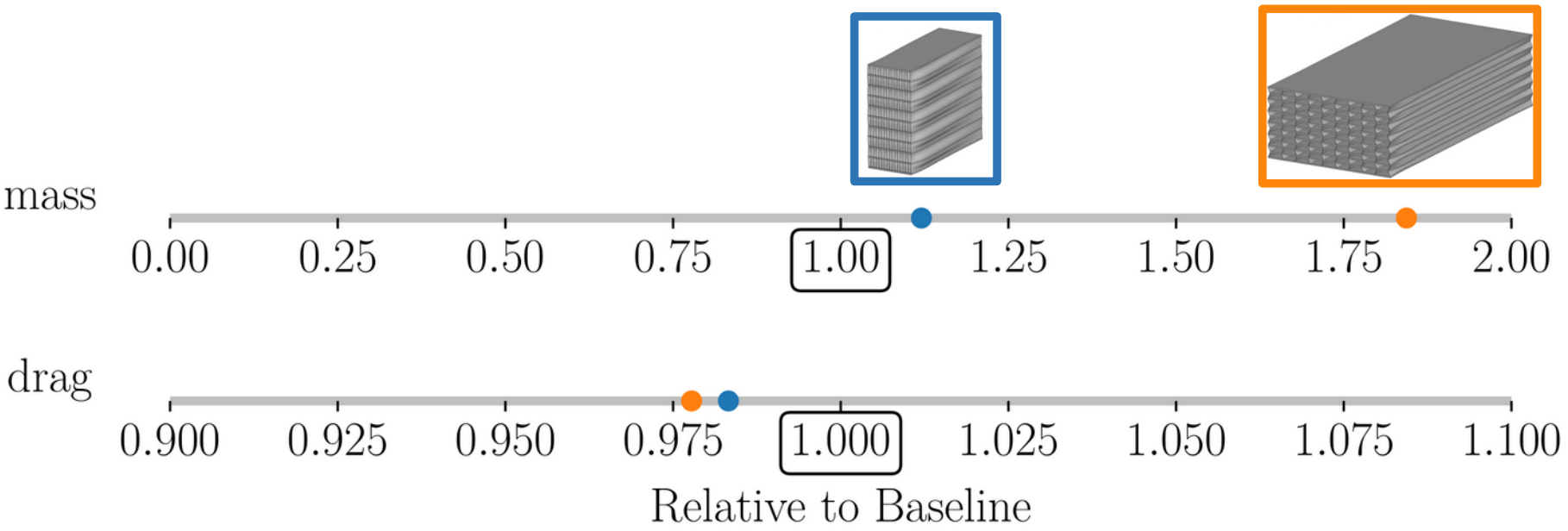
Larger channels reduce the total number of corners



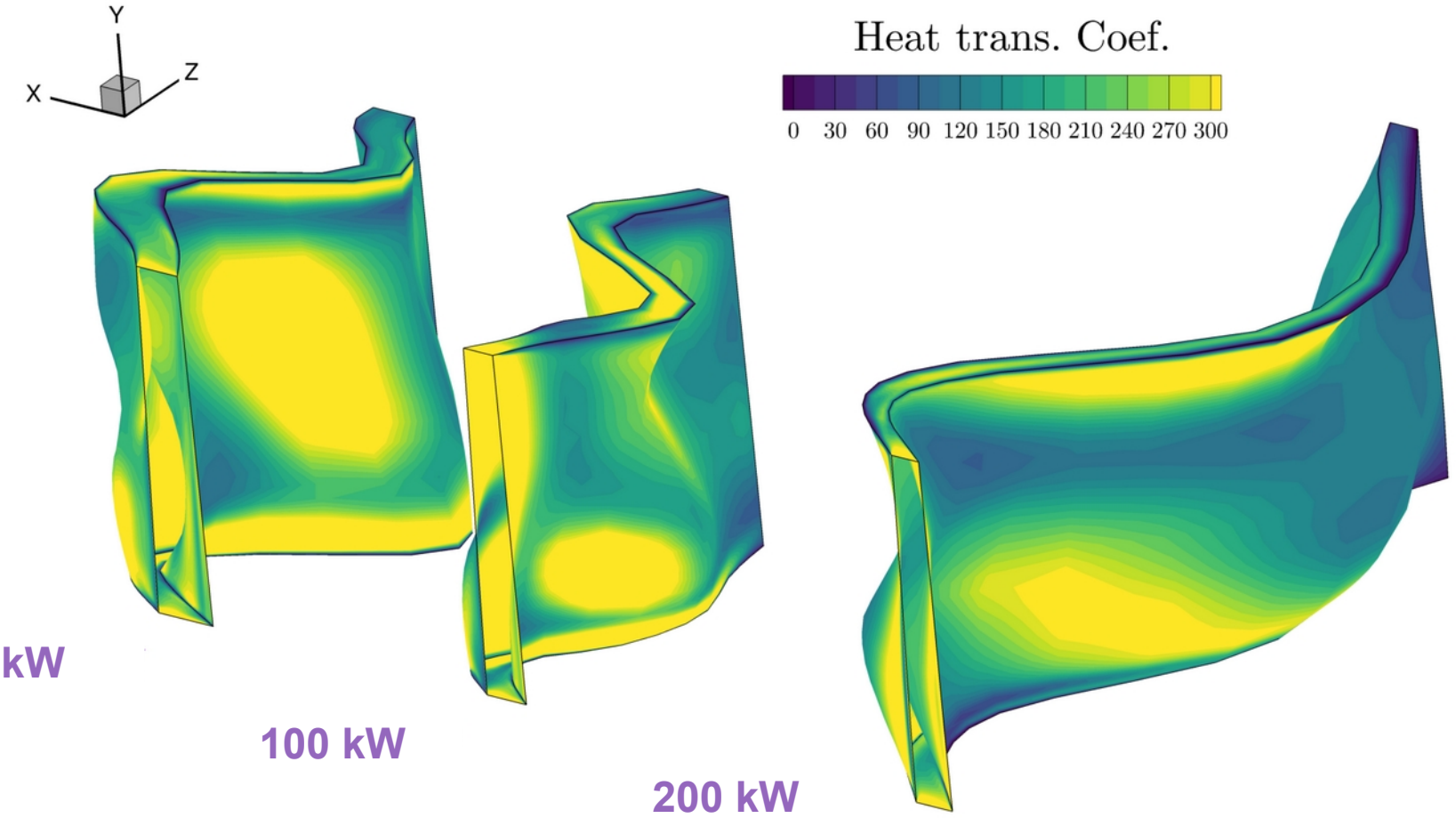
The optimizer reaches different designs when starting from different locations



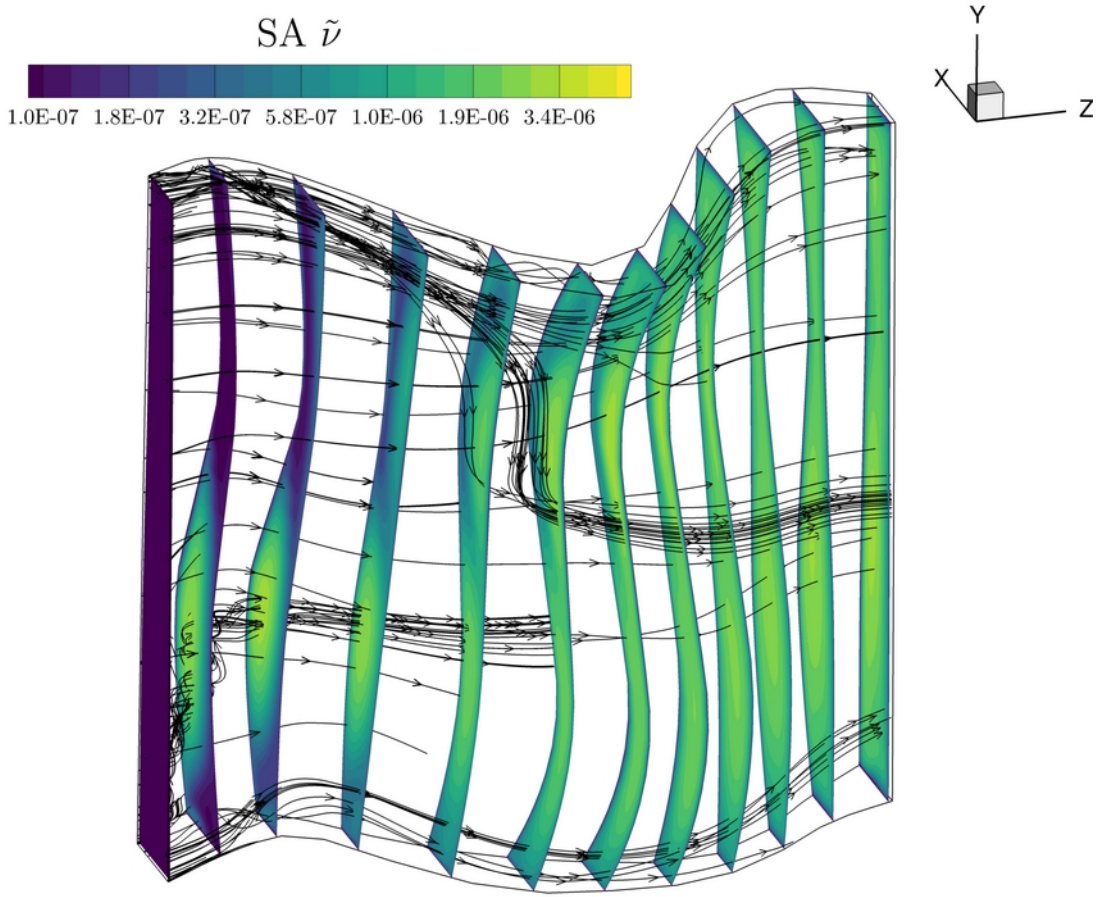
Despite the difference in geometry, the drag is similar



Mass minimizing designs have more hot spots

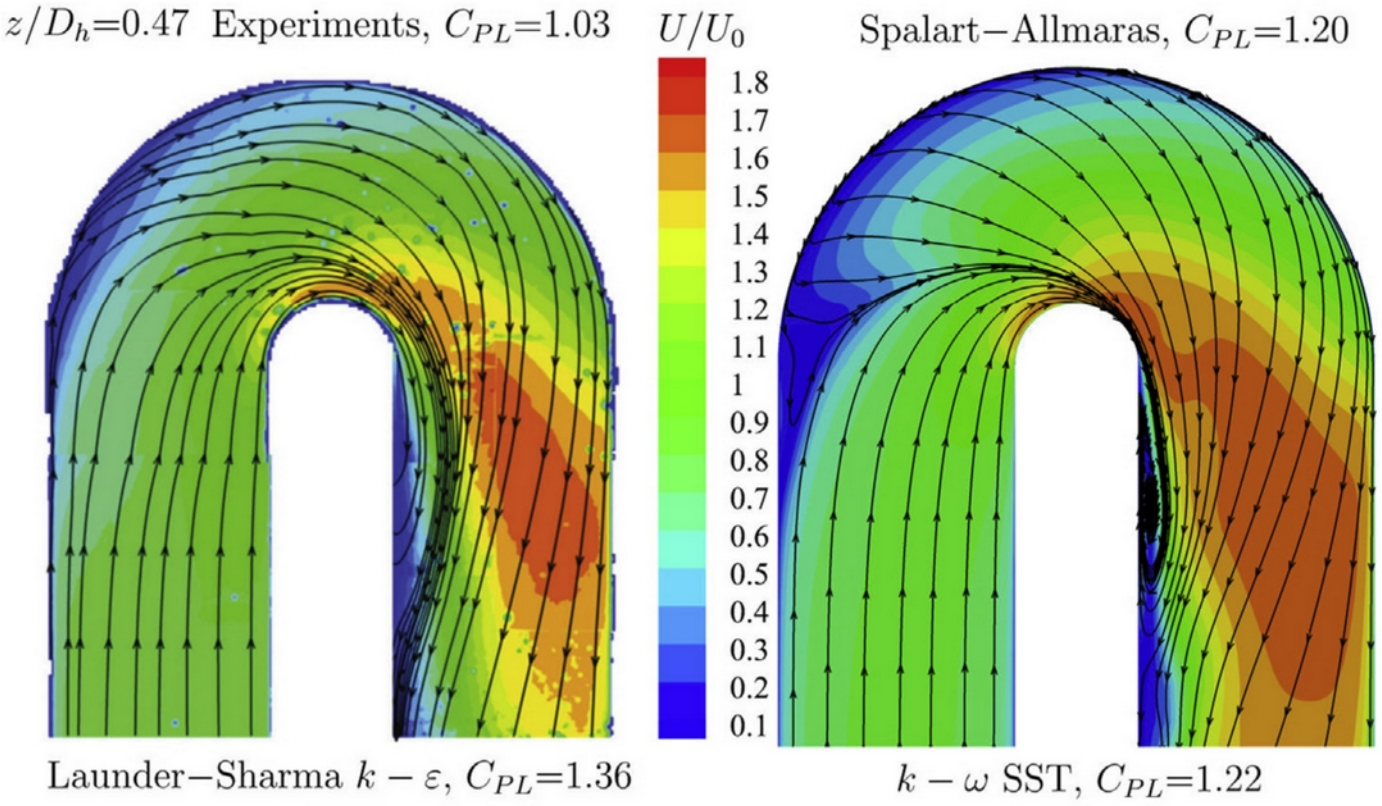


Separation increases turbulent viscosity in channel



100 kW

He et al. showed that SA can predict separation well enough for internal flows



He, Mader, Martins, Maki. **Aerothermal optimization of a ribbed U-bend cooling channel using the adjoint method**. *Aerospace Science and Technology*, 2019

Applied gradient-based shape optimization to plate-fin (Aim 1)

- This work represents the first instance of adjoint-based shape optimization of a plate-fin heat exchanger

Compared affect of objective function and heat load on design (Aim 2)

- The design space for drag was multimodal
- The mass minimizing designs used separation to reduce the required surface area
- Designs optimized for lower heat load used fewer channels of the same design in each layer

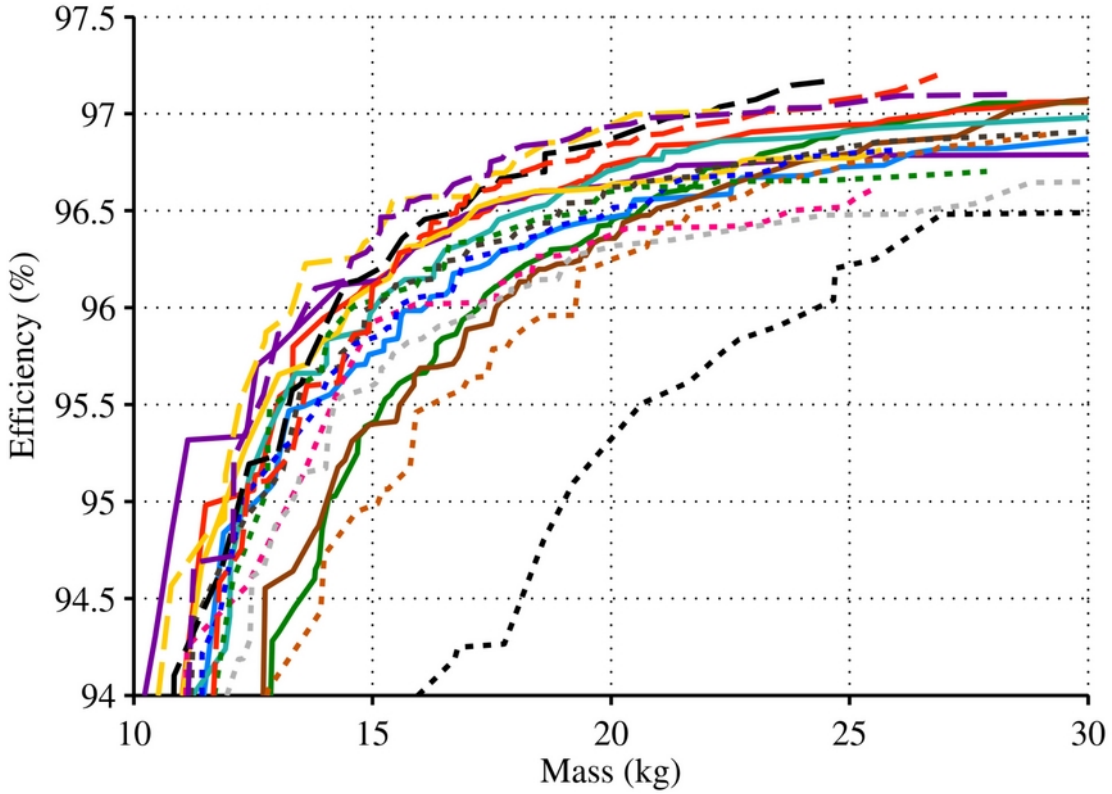
Road map

Open-source Framework for Heat Exchanger Optimization (Aim 3)

Optimization of a Plate-fin Heat Exchanger (Aim 1,2)

Optimization of a Surface Heat Exchanger (Aim 1,2)

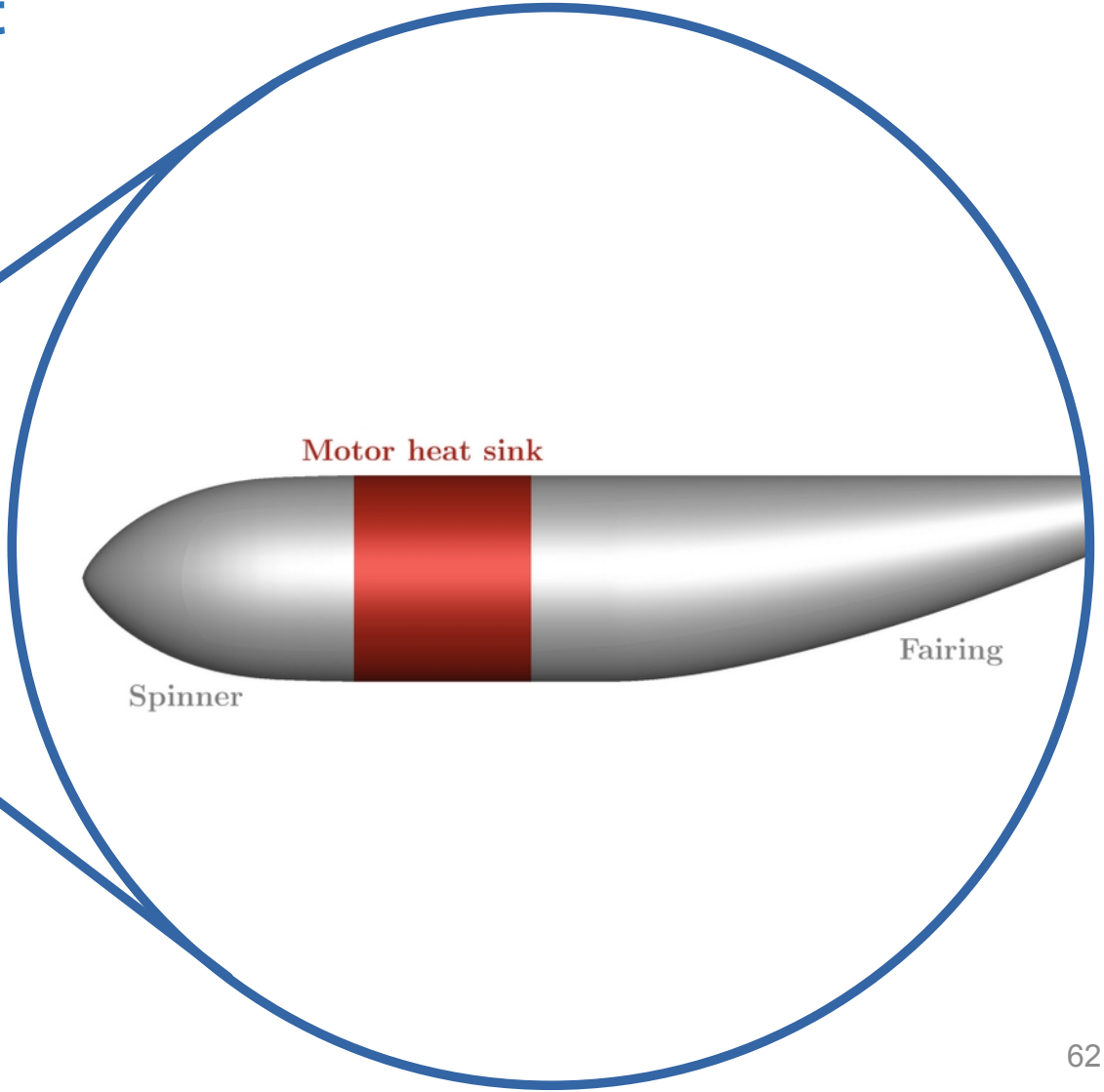
For the same power, a motor with less mass is less efficient



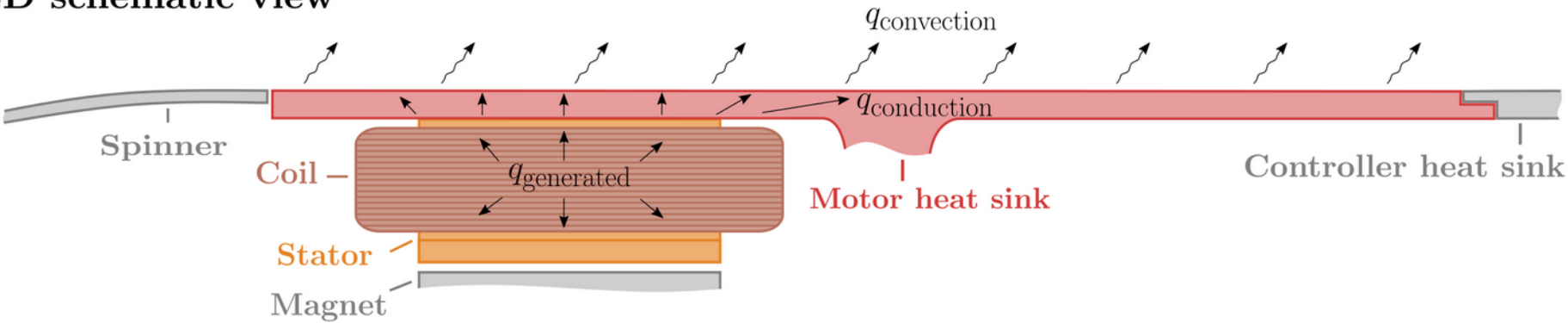
Dubois, van der Geest, Bevirt, Christie, Borer, Clarke
Design of an Electric Propulsion System for SCEPTOR's Outboard Nacelle, 2016

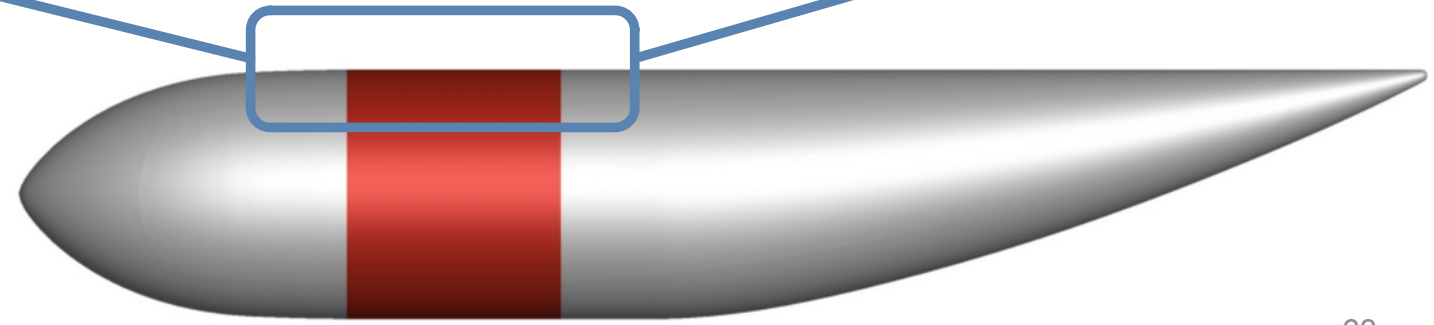
Geometry is the X-57 high-lift nacelle and motor heat sink



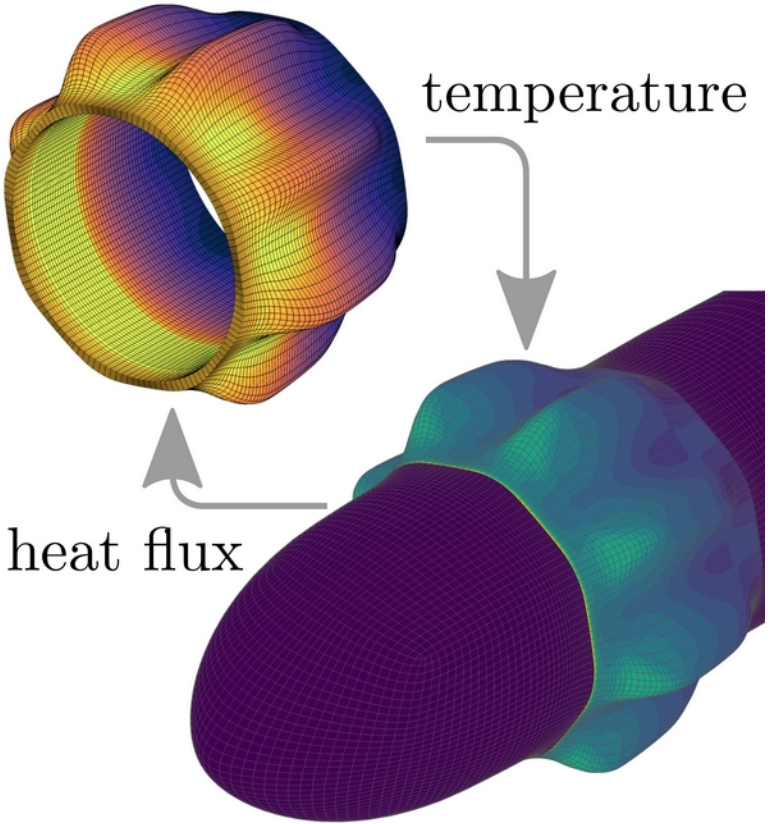


2D schematic view

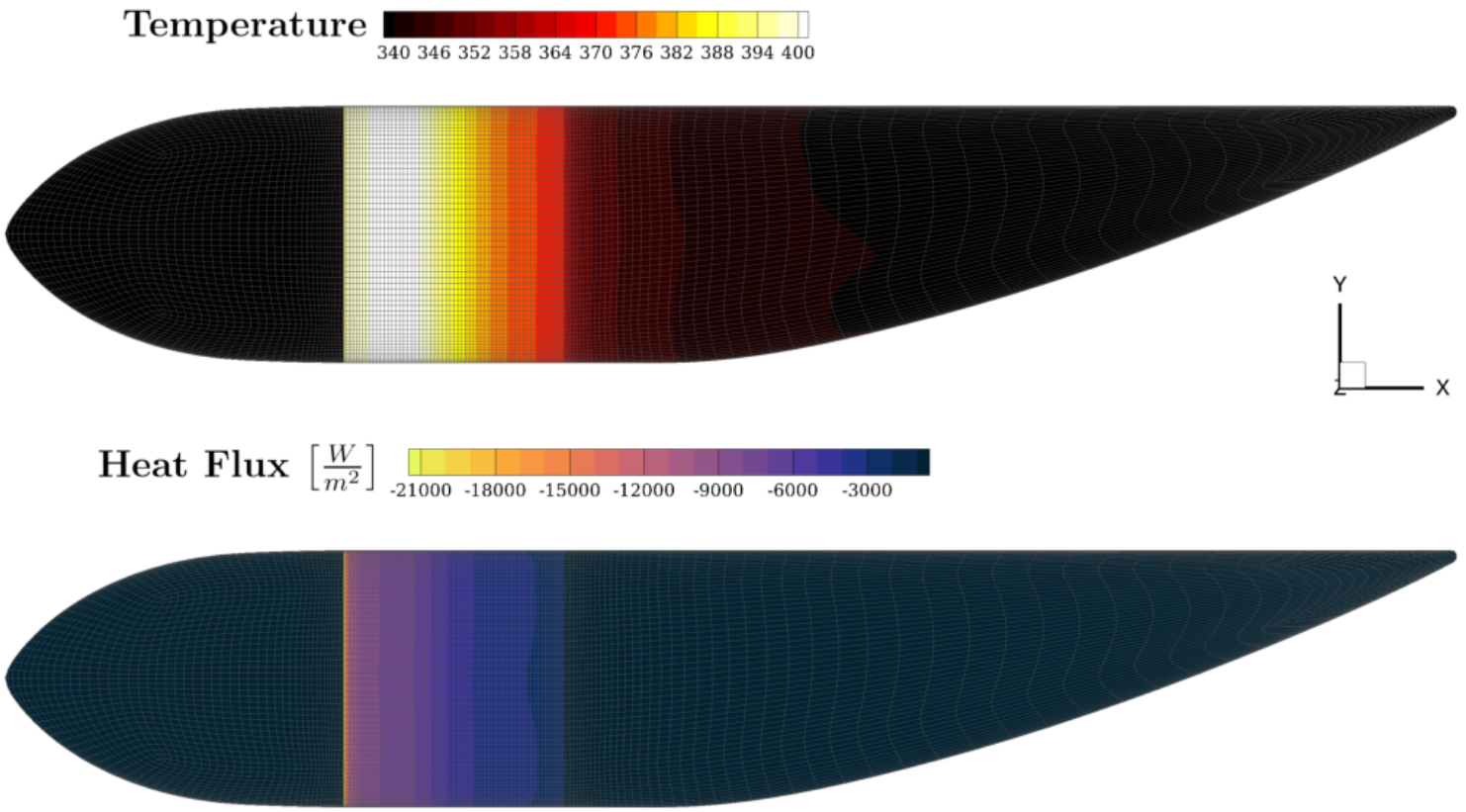




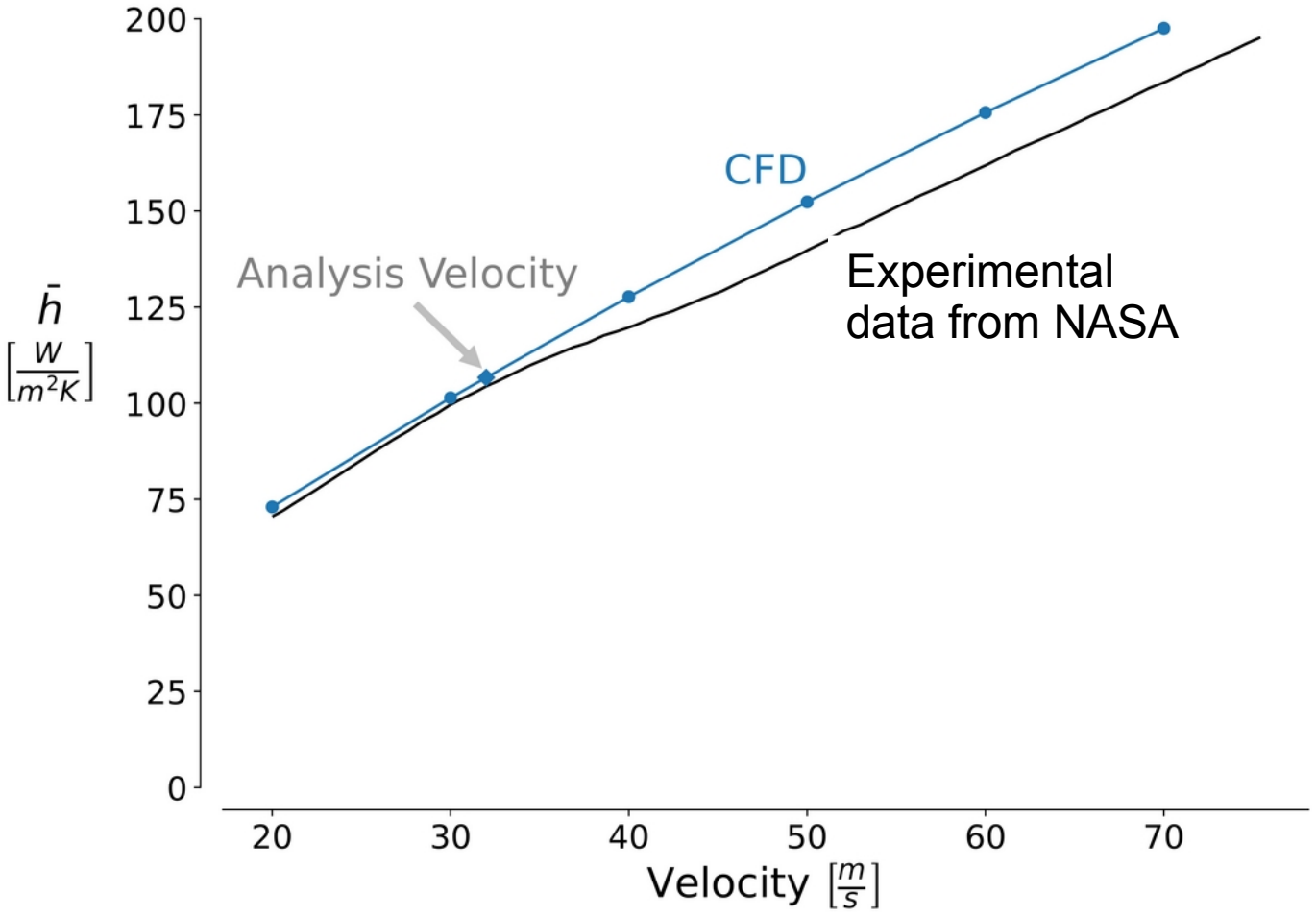
Iteration needed to converge conjugate heat transfer model



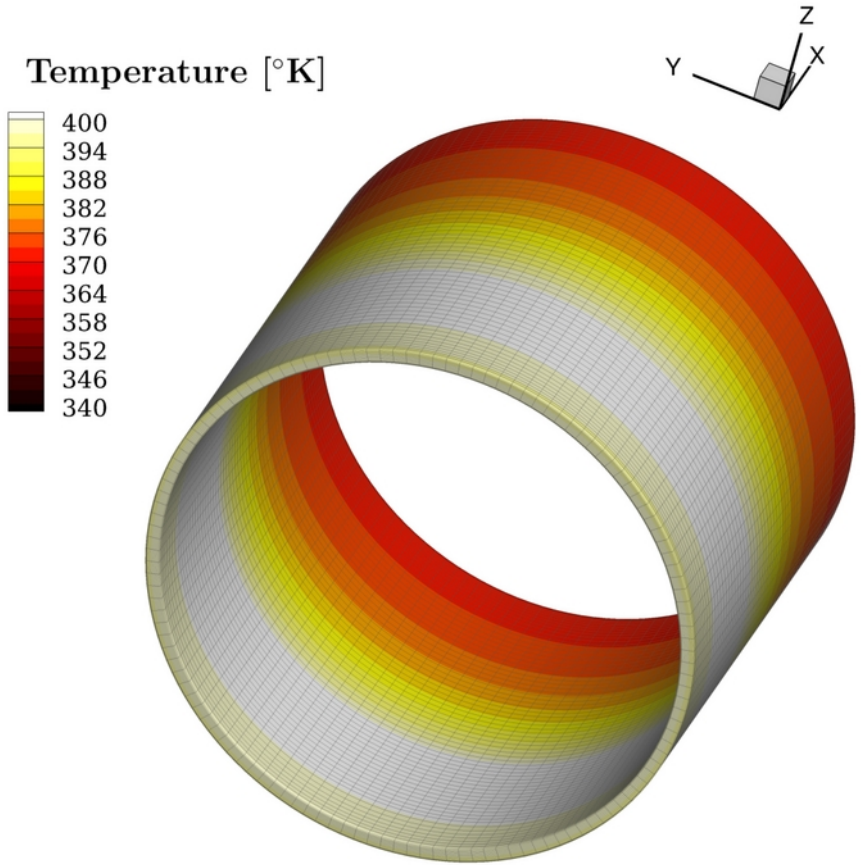
CFD solver, ADflow, computes convective heat flux



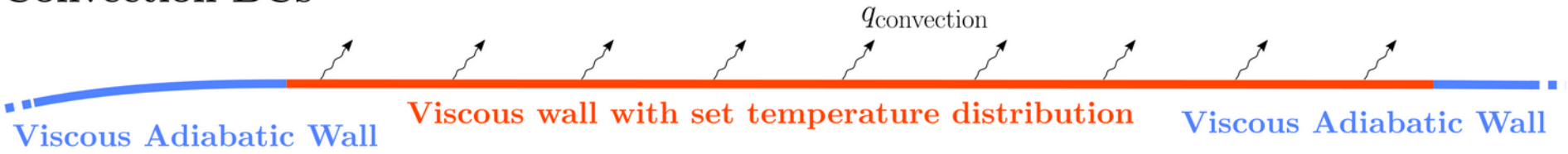
CFD accurate to within 2.5% at analysis velocity



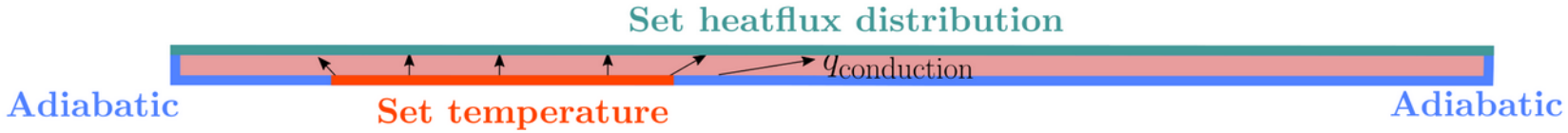
FEM solver, TACS, computes the surface temperature



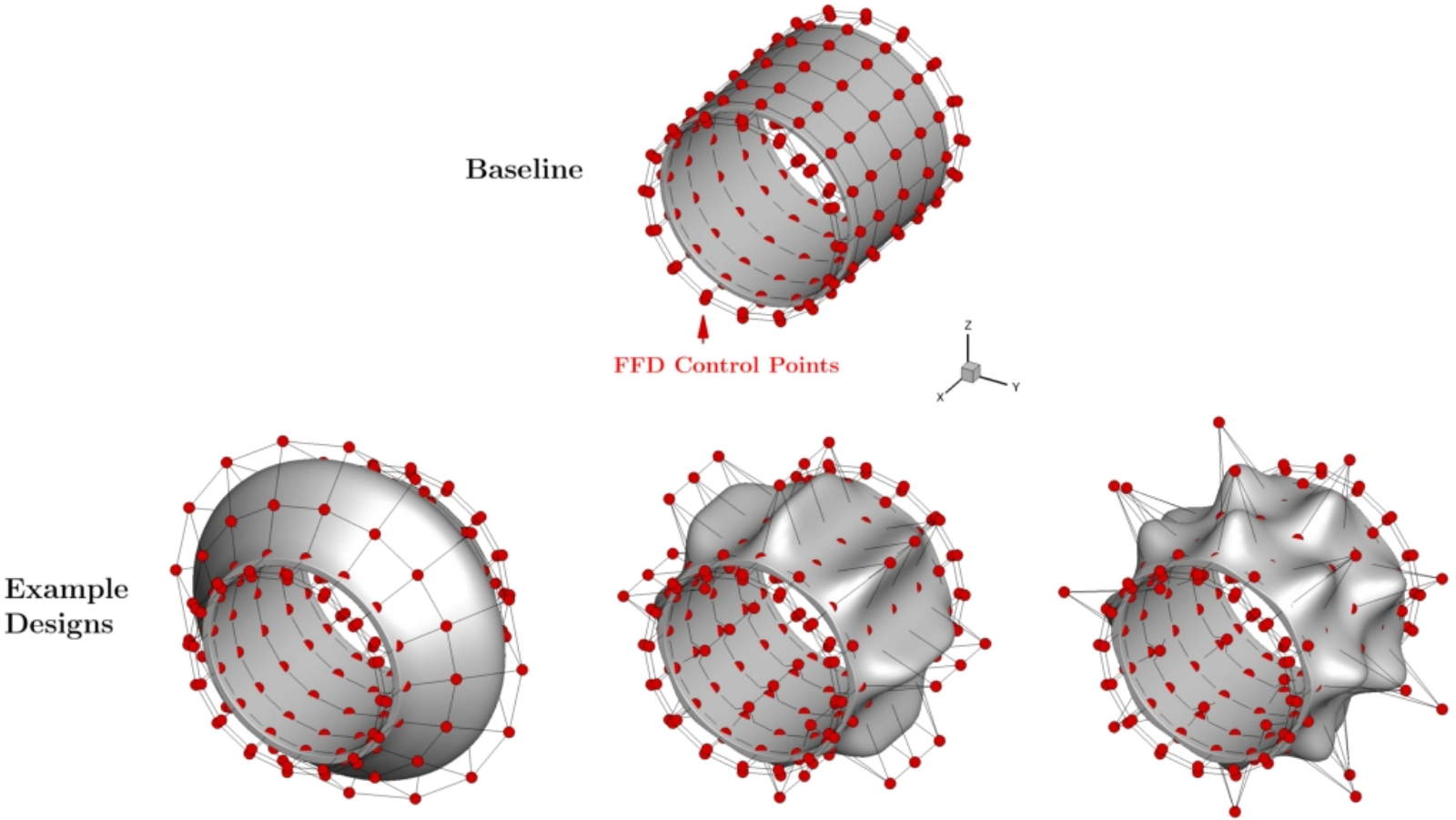
Convection BCs



Conduction BCs



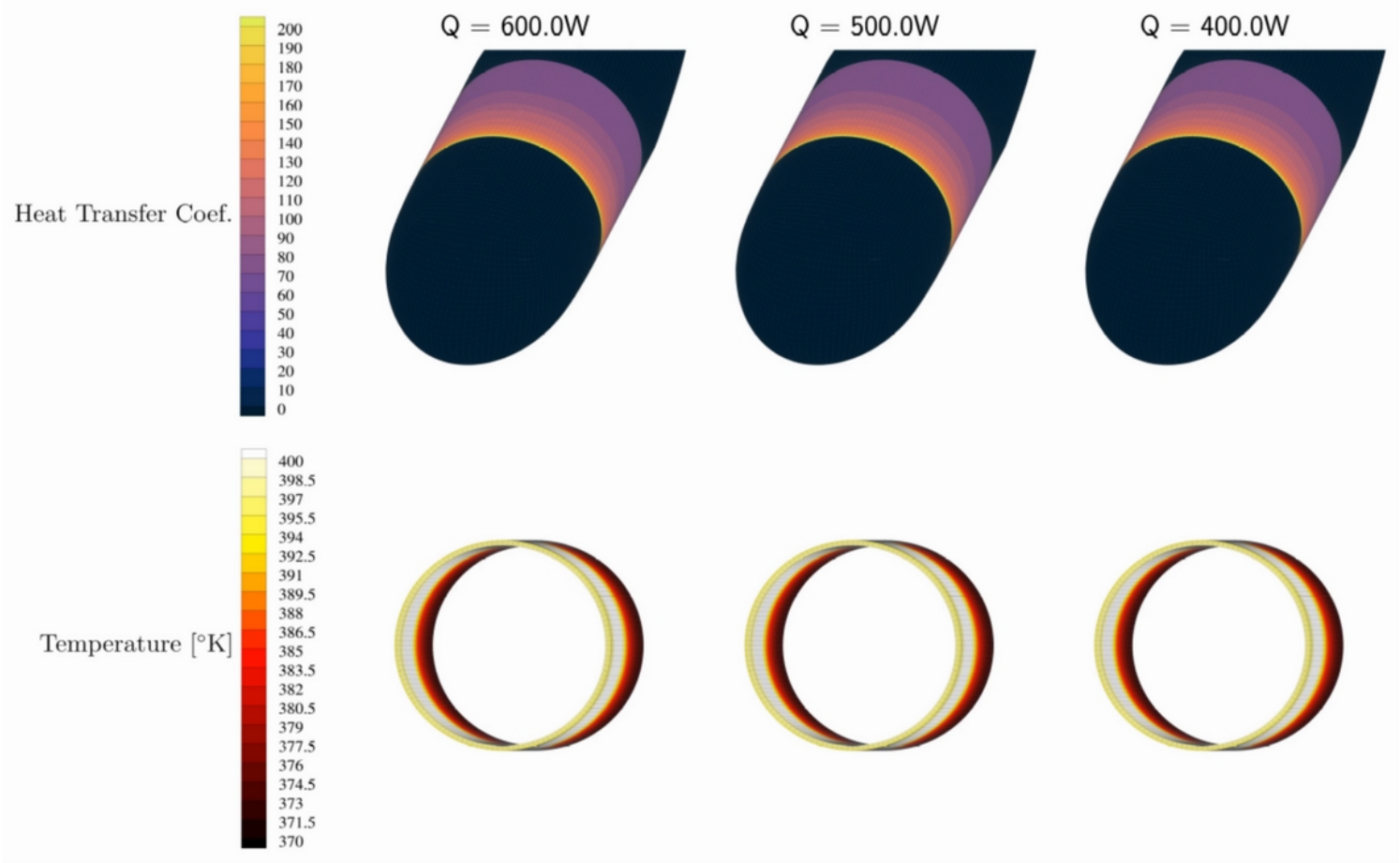
FFD approach is used to parameterize the shape



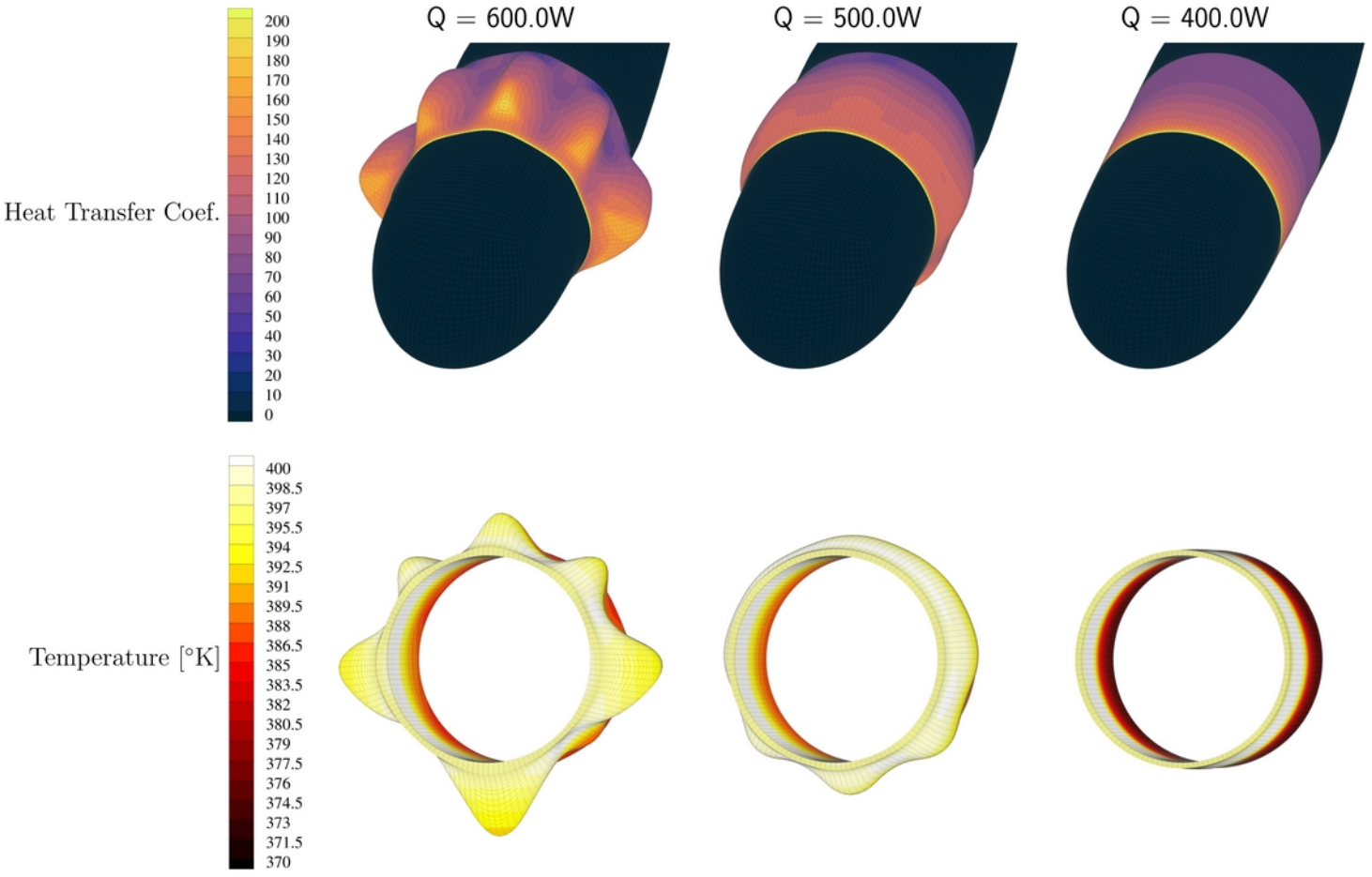
Minimize drag with while meeting heat transfer and thickness constraints

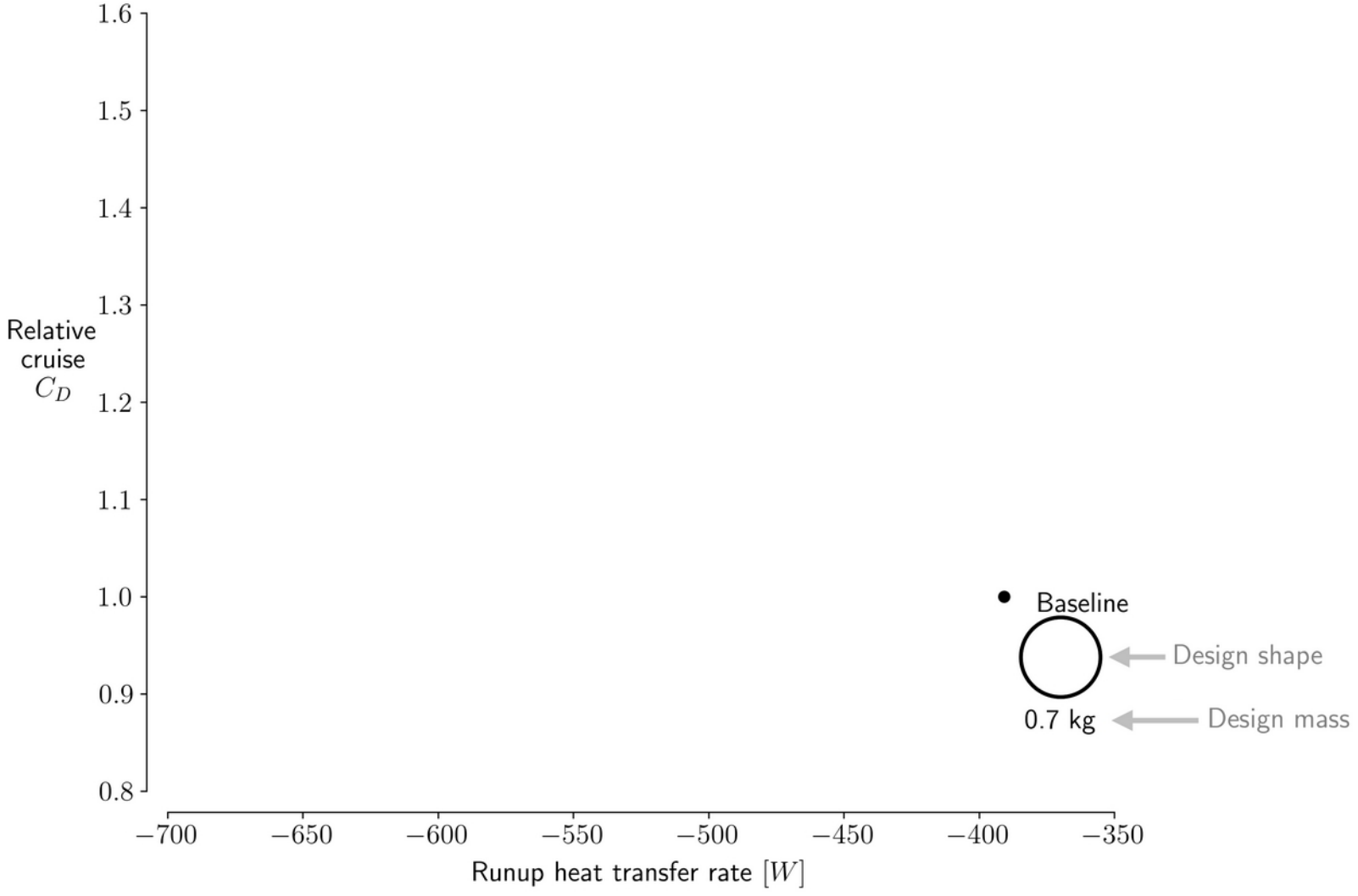
	Variable	description	Quantity
minimize	C_D	Drag coefficient of the nacelle	1
with respect to	r	Radial coordinate of the FFD control points	48
subject to	$\dot{Q} \geq \dot{Q}_{\max}$	Total heat transfer rate during run-up condition is greater than waste heat production	1
	$t \geq \frac{1}{2}t_0$	The thickness is greater than or equal to half the original thickness	756

All optimizations started from the same baseline

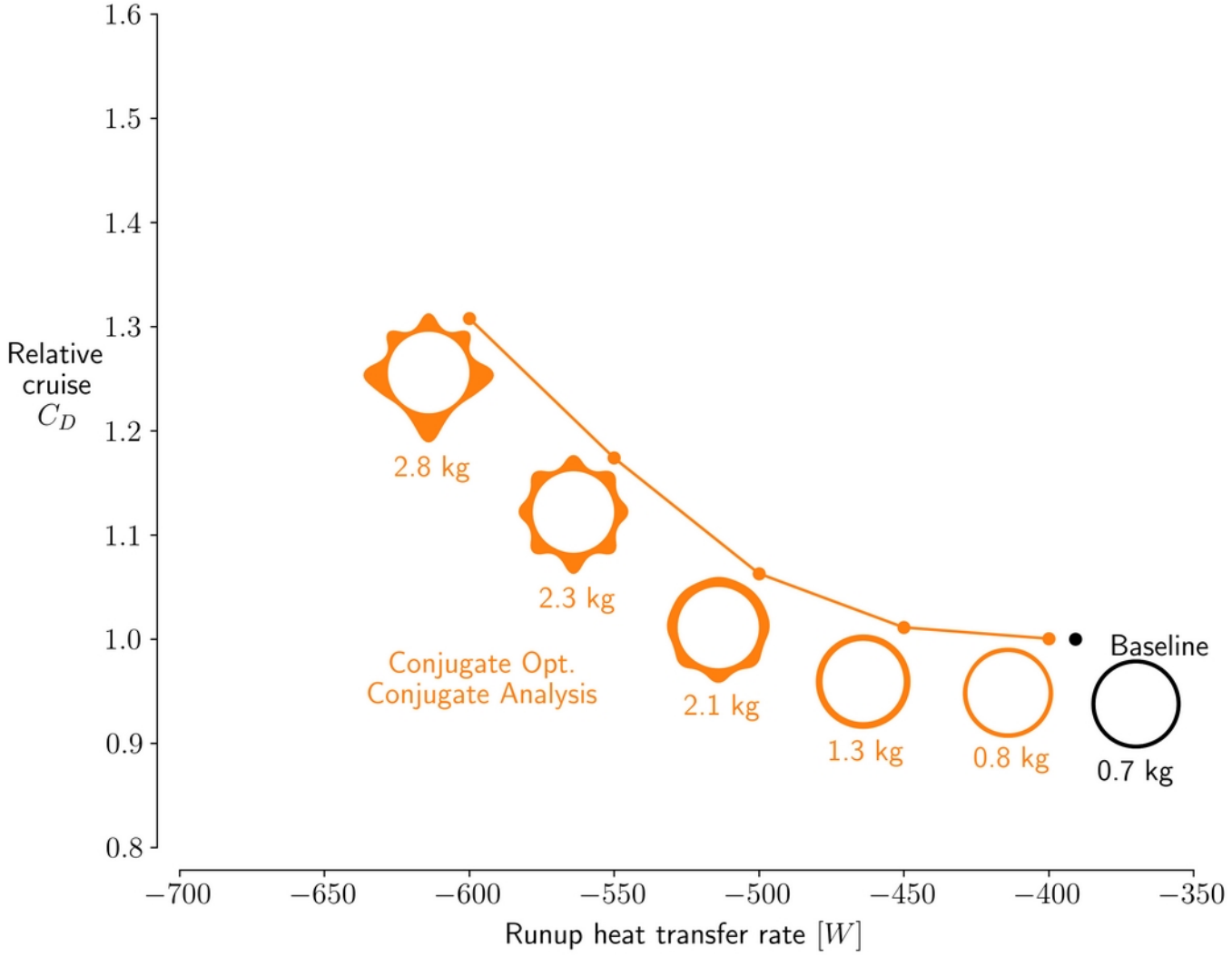


Optimizer adds fins for high heat loads

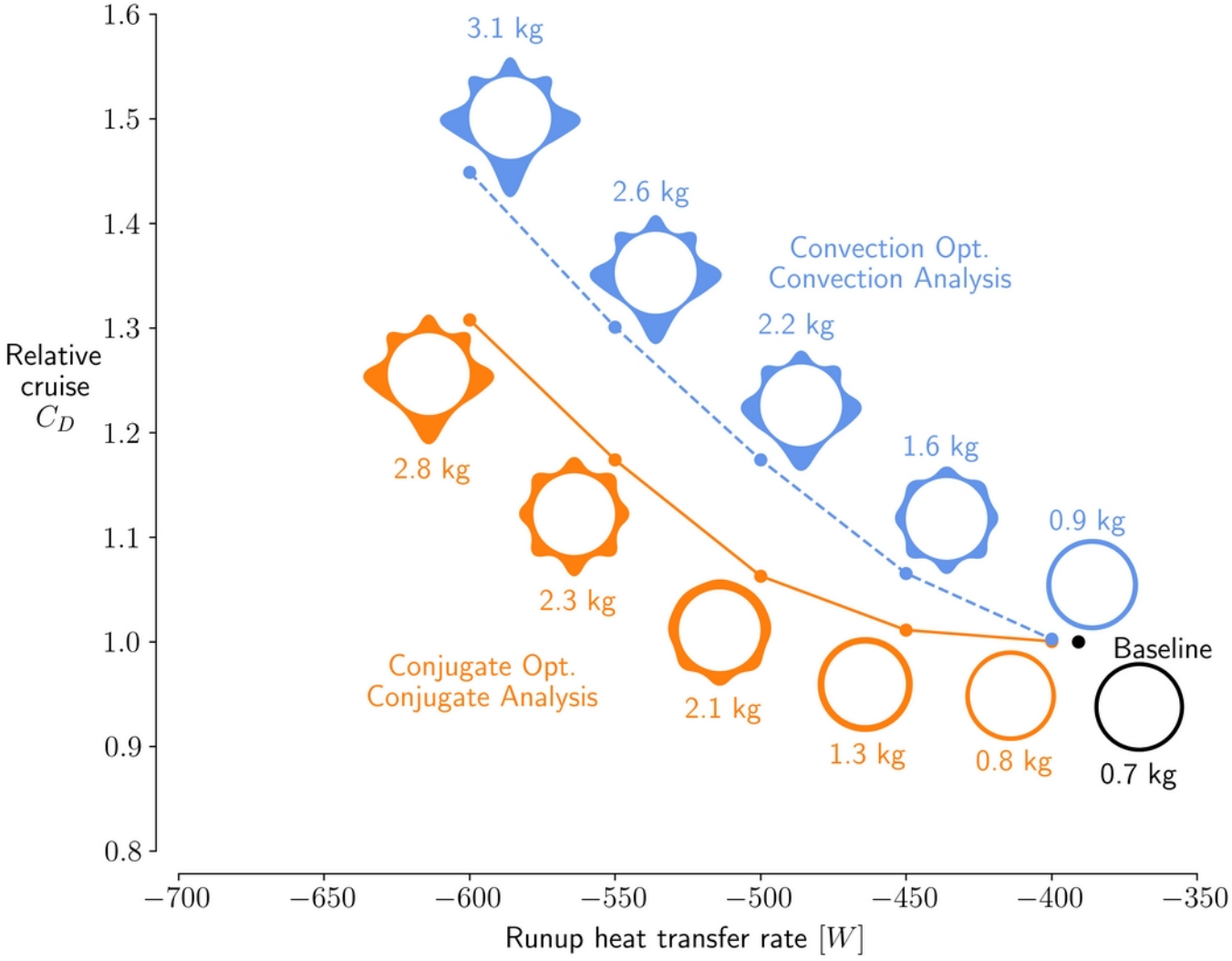



1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
Relative cruise C_D
−700
−650
−600
−550
−500
−450
−400
−350
Runup heat transfer rate $[W]$
Baseline
Design shape
0.7 kg
Design mass

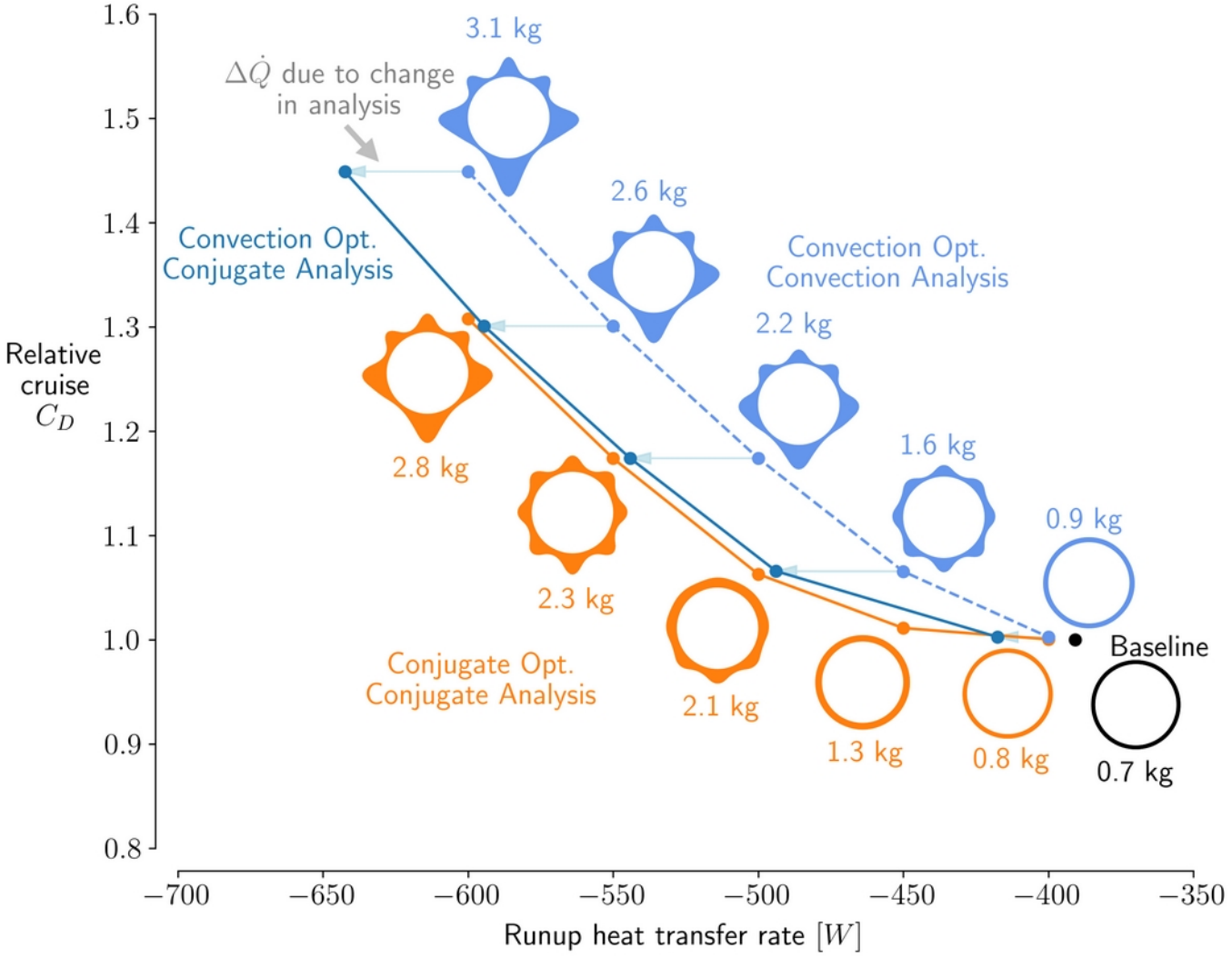
Fins first develop on the bottom



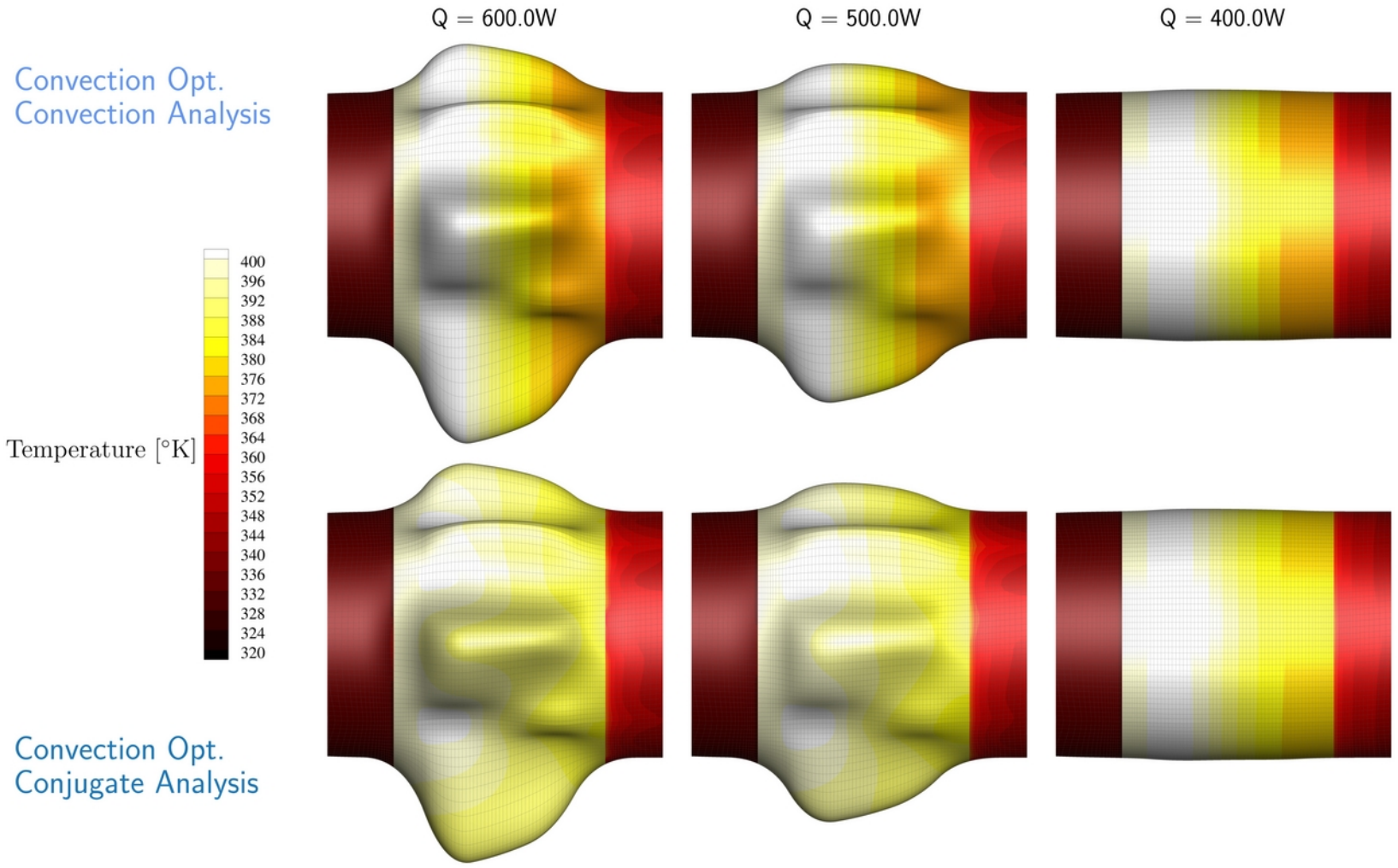
Convection-only optimized designs are larger



Convection-only analysis under predicts heat transfer



Under prediction caused by neglecting aft conduction



Applied gradient-based shape optimization to surface Hx (Aim 1)

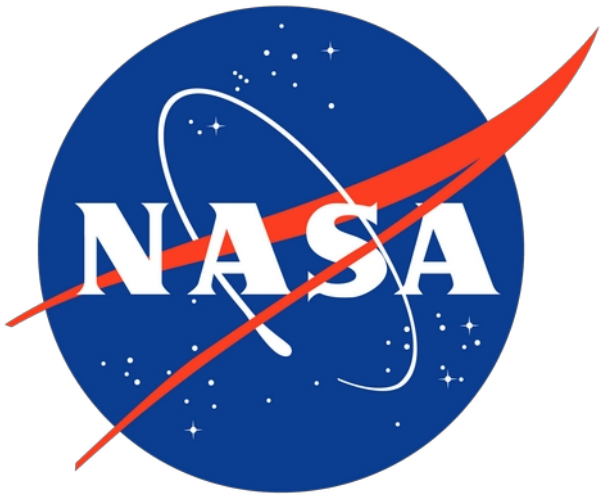
First instance of adjoint-based shape optimization of a surface heat exchanger

Compared the affect of heat transfer model and load on design (Aim 2)

As the heat load increased, the heat exchanger develops extended surfaces

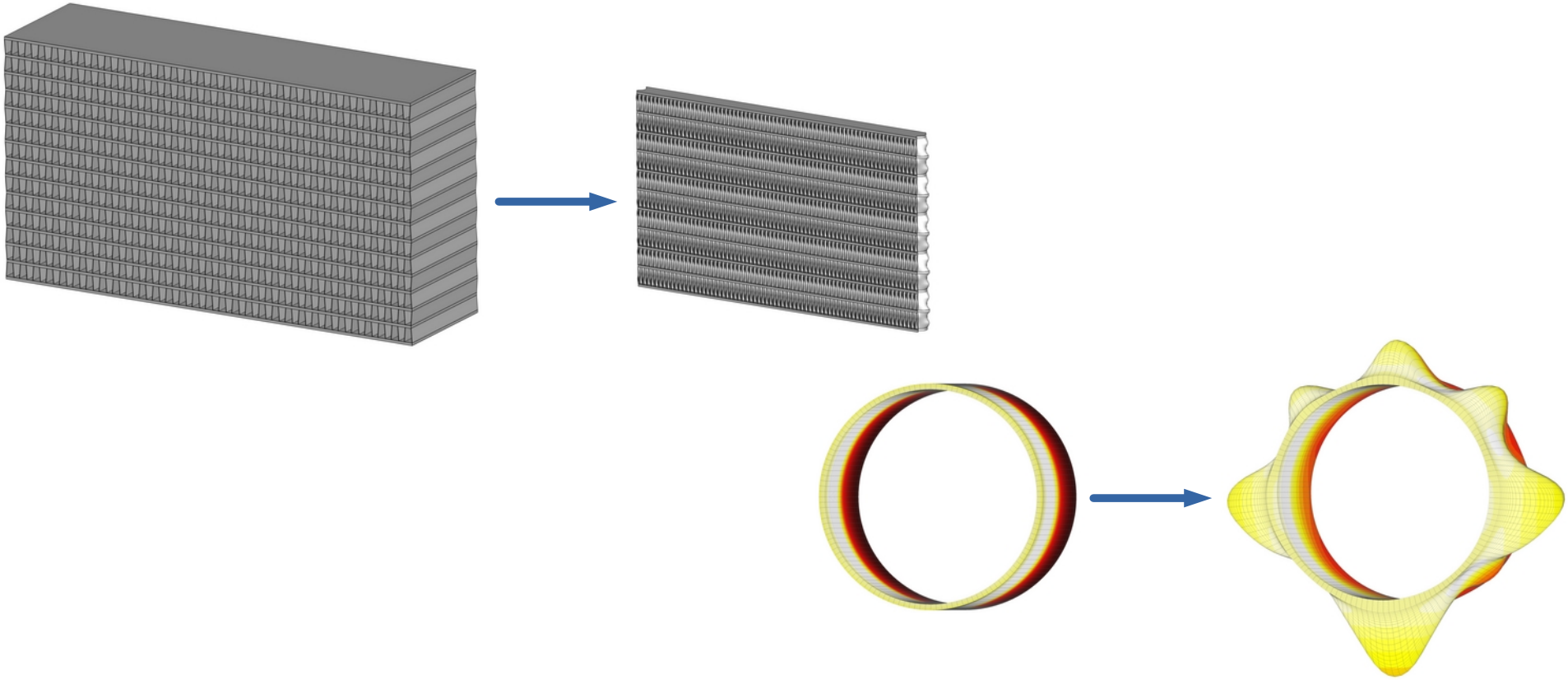
The convective model lead to similar, but larger designs.

NASA funded this work



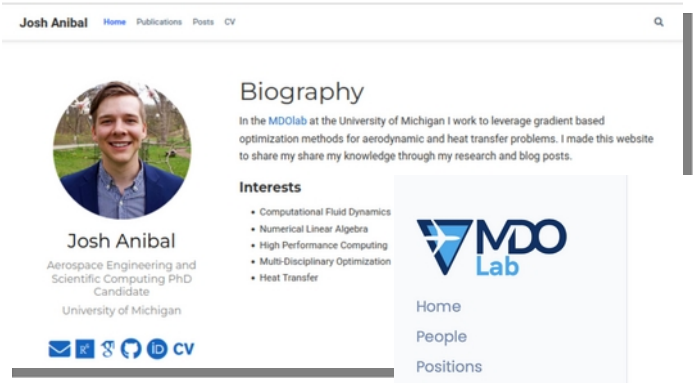
NASA funded this work through the Advanced Air Transport Technology (AATT) and Transformational Tools and Technologies (TTT) projects

What are your questions?



To find information on related work see...

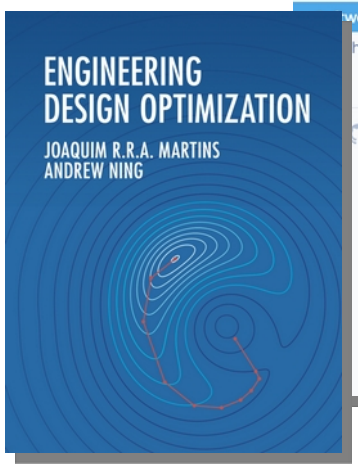
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Backup slides

title