

Calorimeter Heat Flux Trends in NASA's Subscale Rotating Detonation Rocket Engine

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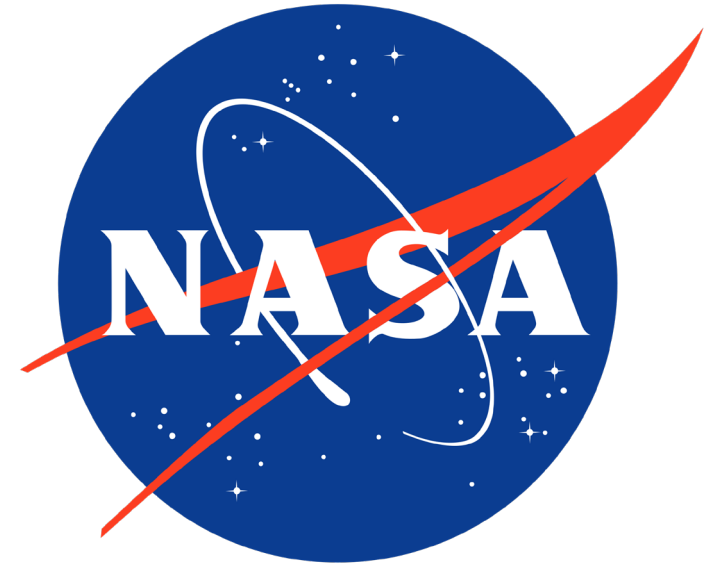
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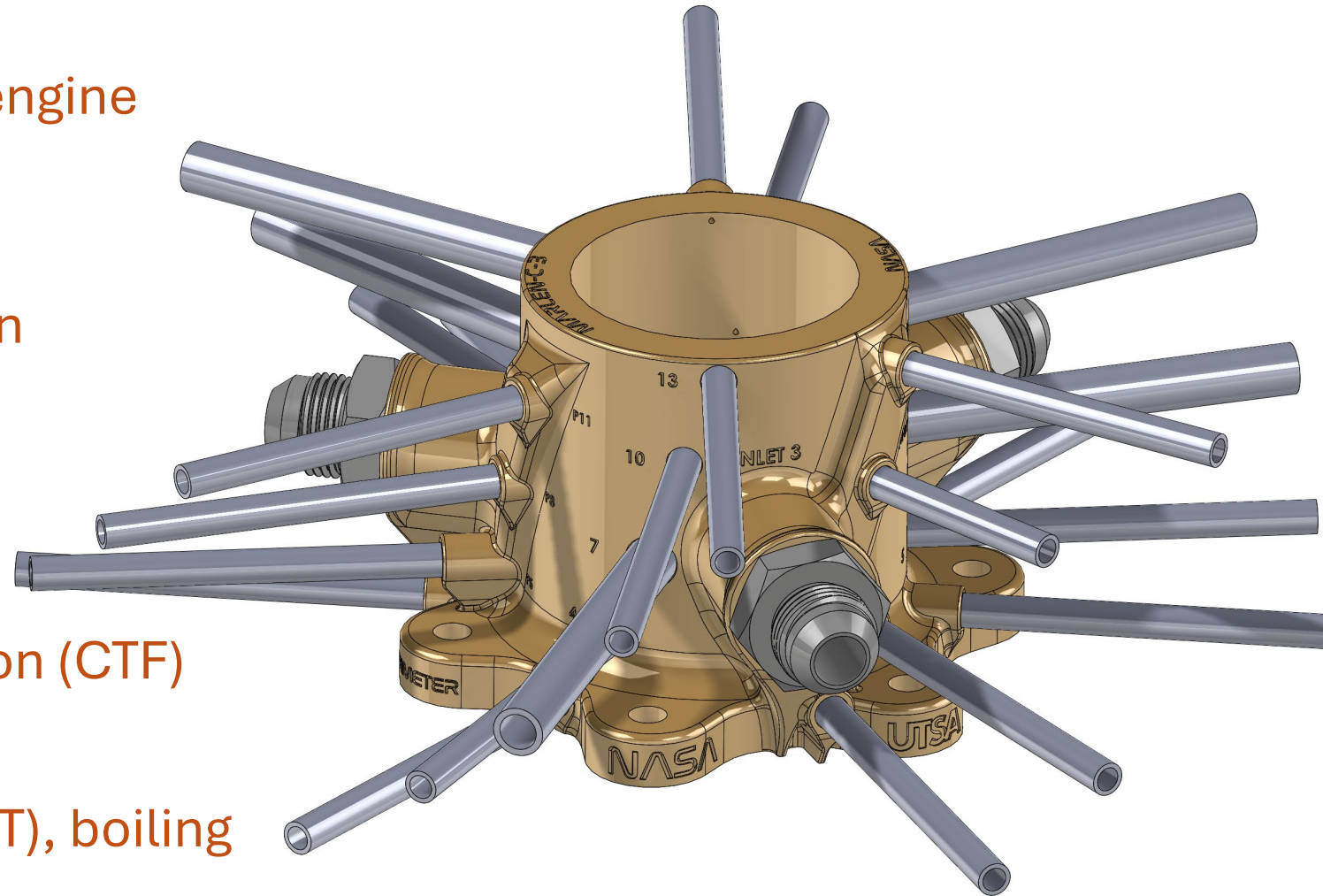
UTSA Engineering

Acknowledgements

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- NASA MSFC ET10 testing team, the Dannys, and east test area weld shop for preparation of hardware
- Ari Goldman and Michaela Hemming for additional data collection activities during test campaign



- **Background/Motivation**
 - Rotating detonation rocket engine (RDRE) heat transfer
- **Design**
 - Calorimeter hardware design
 - Experimental setup
- **Heat Flux Trends**
- **Data Transformation**
 - Calorimeter Transfer Function (CTF)
- **Computational Analysis**
 - Conjugate heat transfer (CHT), boiling
- **Future Work**



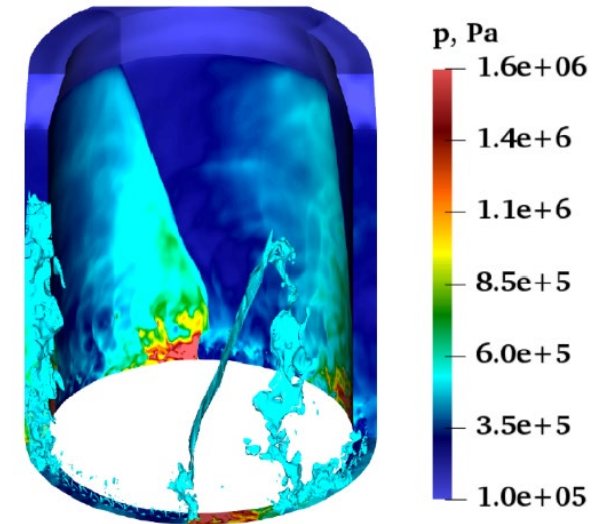
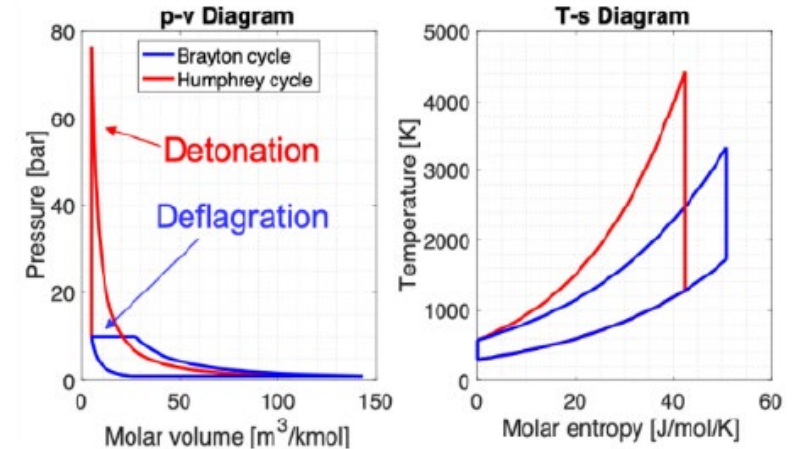
Background

- Detonation-based combustion
 - Benefit space mission architectures
 - Lower entropy (s) → same work for smaller combustor size vs. deflagration

Low Technology Readiness Level (TRL)

- Detonation heat transfer
 - Higher temperature (T)
 - Periodic heating in RDRE walls
 - Varies with configuration and operational setpoint
 - No known heat transfer (HT) correlations (e.g., Bartz)

Cannot calculate HT → remain low-TRL



Demystify RDE/RDRE Heat Transfer

- Canonical msmt: conduction
- Limited test time (<1000 ms)
- Limited spatial resolution

→ No steady-state trends

- Excellent spatial resolution
- Limited test time (<1000 ms)
- Requires calibration

→ No steady-state trends

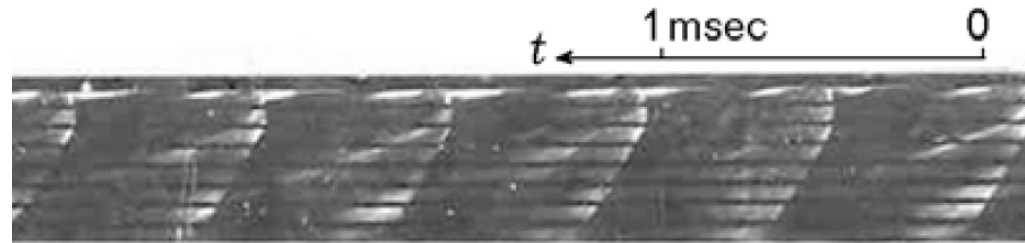
- Excellent test time (∞)
- Limited spatial resolution
- Real estate for sensors

→ Limited local trends

Heat Sink
(heavy copper)

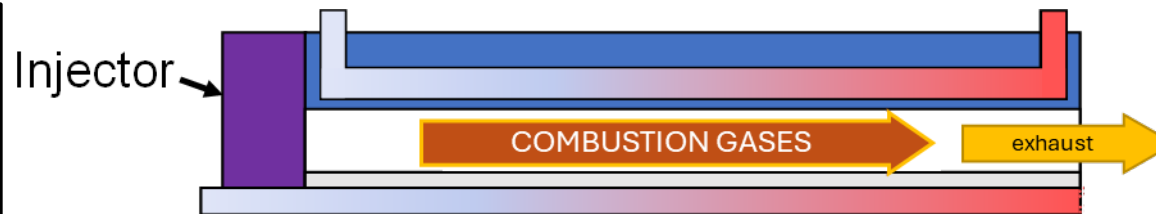


Optical
(glass or plastic chamber)



Bykovskii et al. (2009)

Axial Channel
(actively-cooled, bulk inlet/outlet)



To advance TRL, require steady-state (SS) local heat flux trends

Calorimeter Design

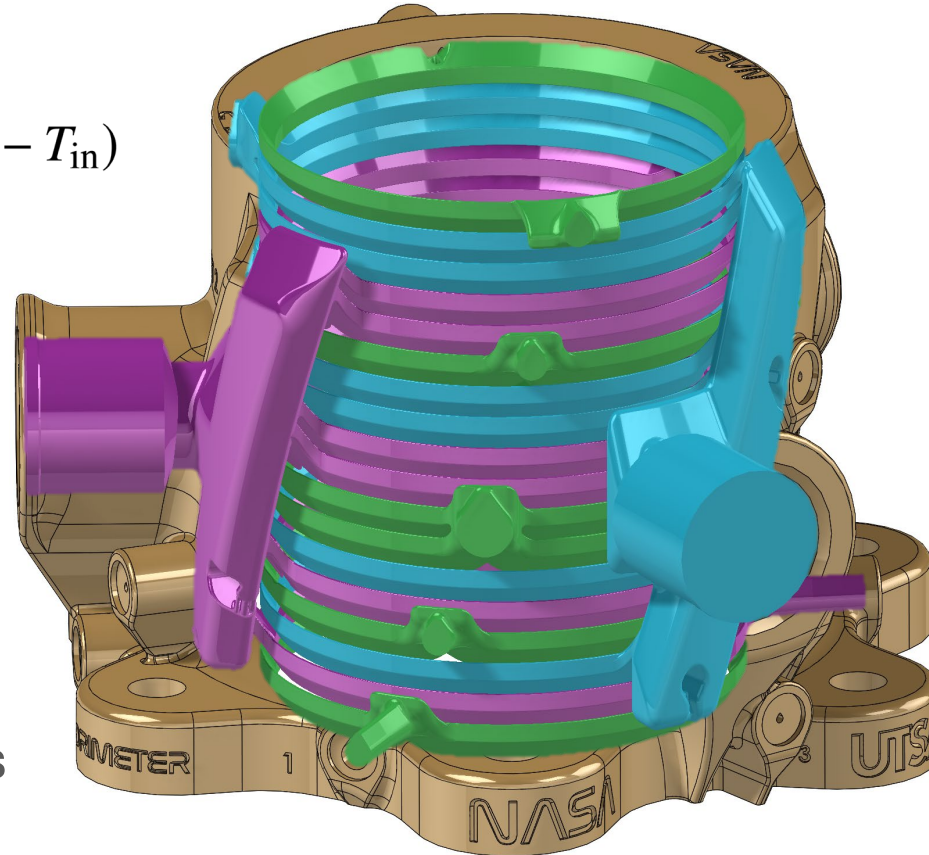
- Circumferential channels
 - Enthalpy difference

$$q'' = \frac{\dot{Q}}{A} \quad \dot{Q} = \dot{m}\Delta h \approx \dot{m}\bar{c}_p(T_{\text{out}} - T_{\text{in}})$$

Local heat flux (q'')

- 3 in. length
- **13 heat flux stations**
 - 8 single-channel
 - 5 double-channel
 - 3 manifolds/6 channels
- **9 chamber pressure**
 - Capillary tube attenuated pressure (CTAP)

Steady-state cooling



MANIFOLD 1	
Station #	Channel #
1	1
4	4
7	7
7	8
10	13
13	18

MANIFOLD 2	
Station #	Channel #
2	2
5	5
8	9
8	10
11	14
11	15

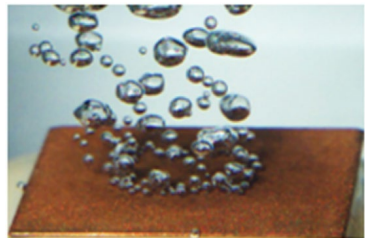
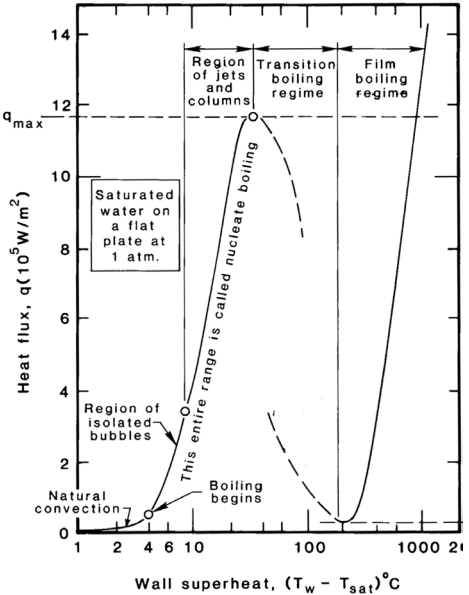
MANIFOLD 3	
Station #	Channel #
3	3
6	6
9	11
9	12
12	16
12	17

Coolant Channel Design

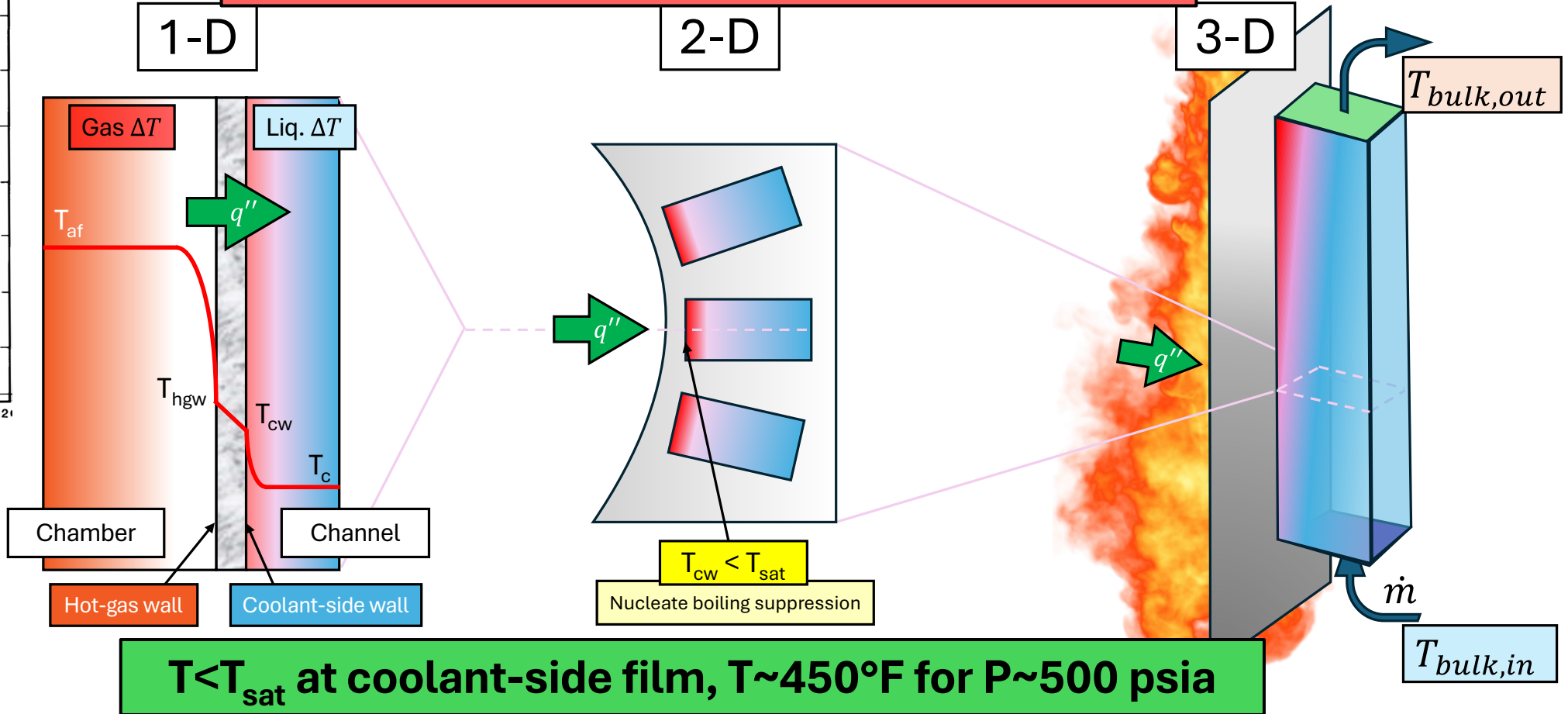
Nucleate boiling: locally-enhanced heat transfer

Potential for error in $dT \rightarrow q''$ measurement

Lienhard V et al. (2018)



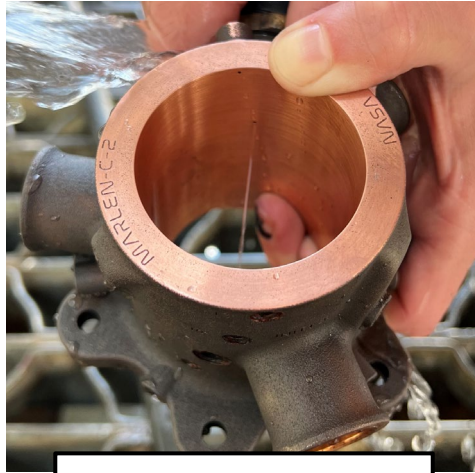
Wang et al. (2022)



$T < T_{sat}$ at coolant-side film, $T \sim 450^\circ\text{F}$ for $P \sim 500 \text{ psia}$

Experimental Setup and Test

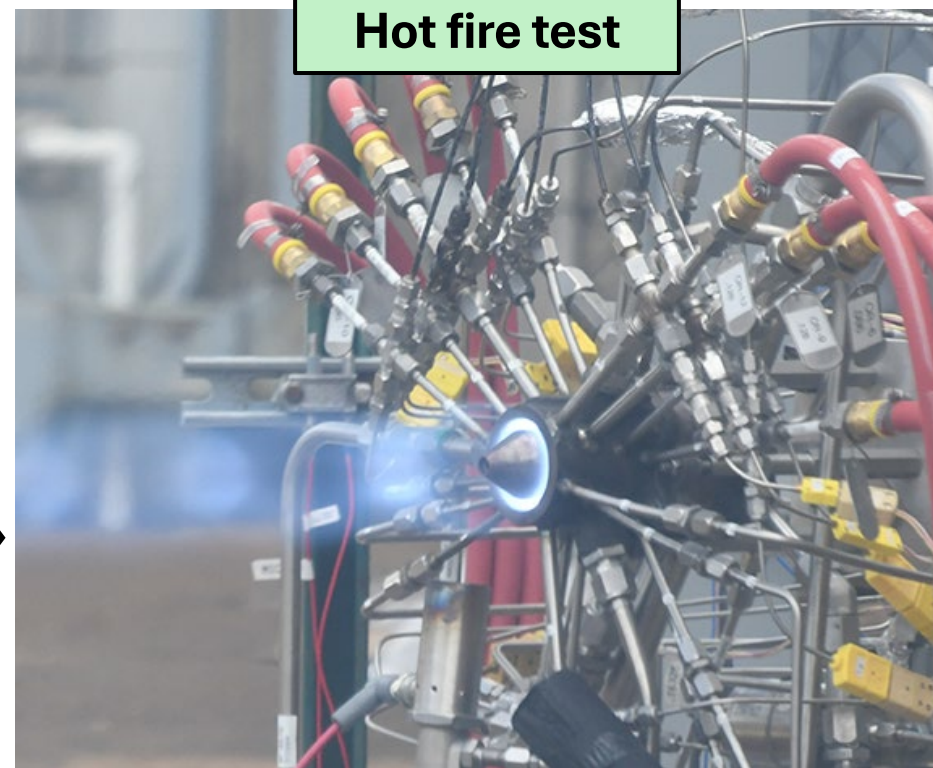
AM GRCo-42, post-HIP



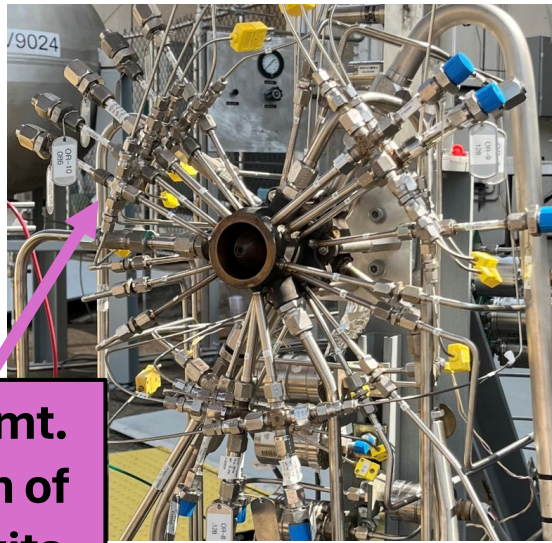
As-machined



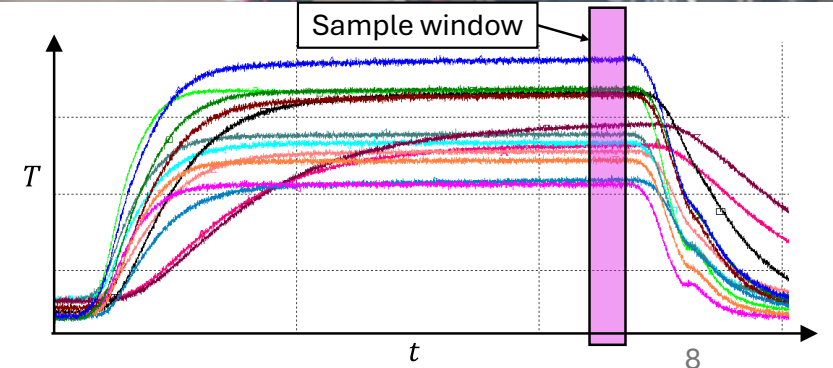
Hot fire test



P & T msmt. upstream of orifice exits



Joseph Hernandez-McCloskey





Heat Flux Trends vs. Conditions

Overall Data

- 3 of 44 tests below 100 psia Pc

heat flux

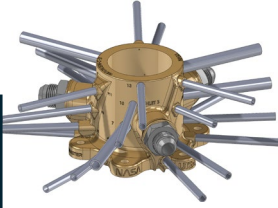
Per station

$$q'' = \frac{\dot{Q}}{A}$$

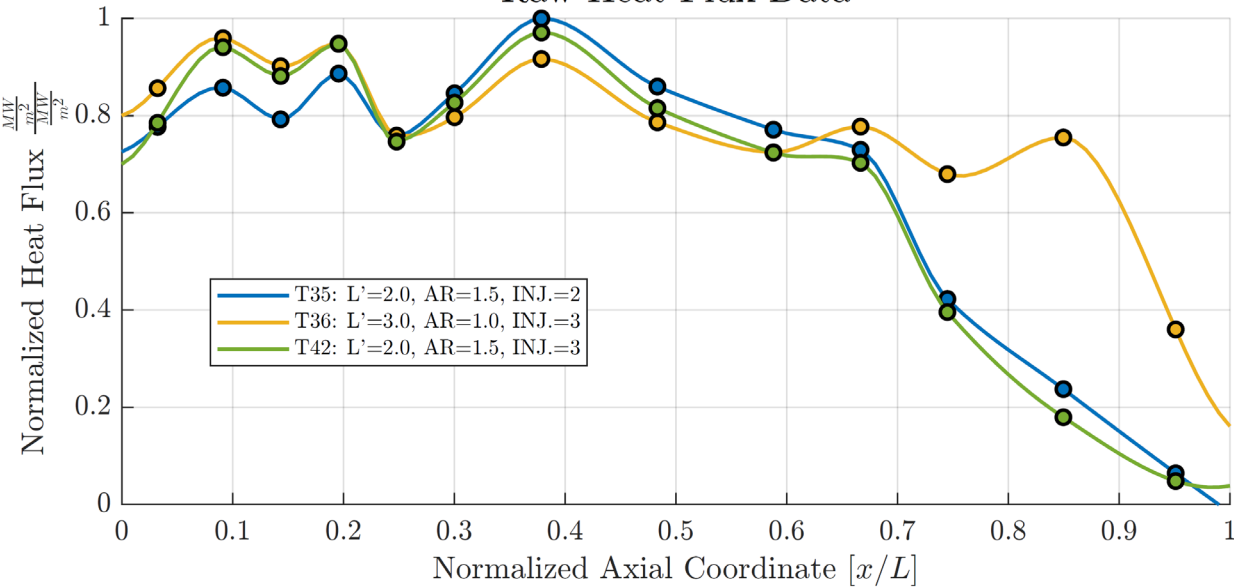
specific energy into wall

Per station

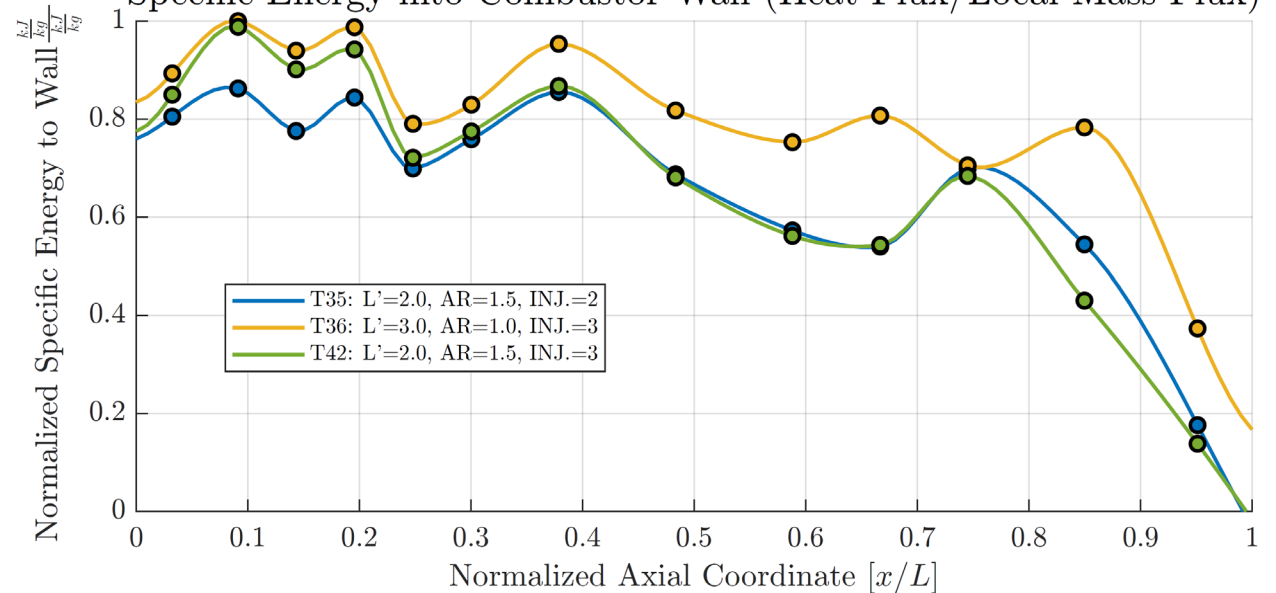
$$e = \frac{q''}{\dot{m}/A_{local}}$$



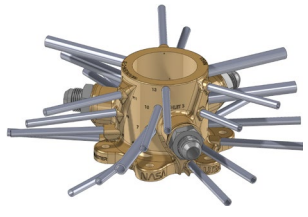
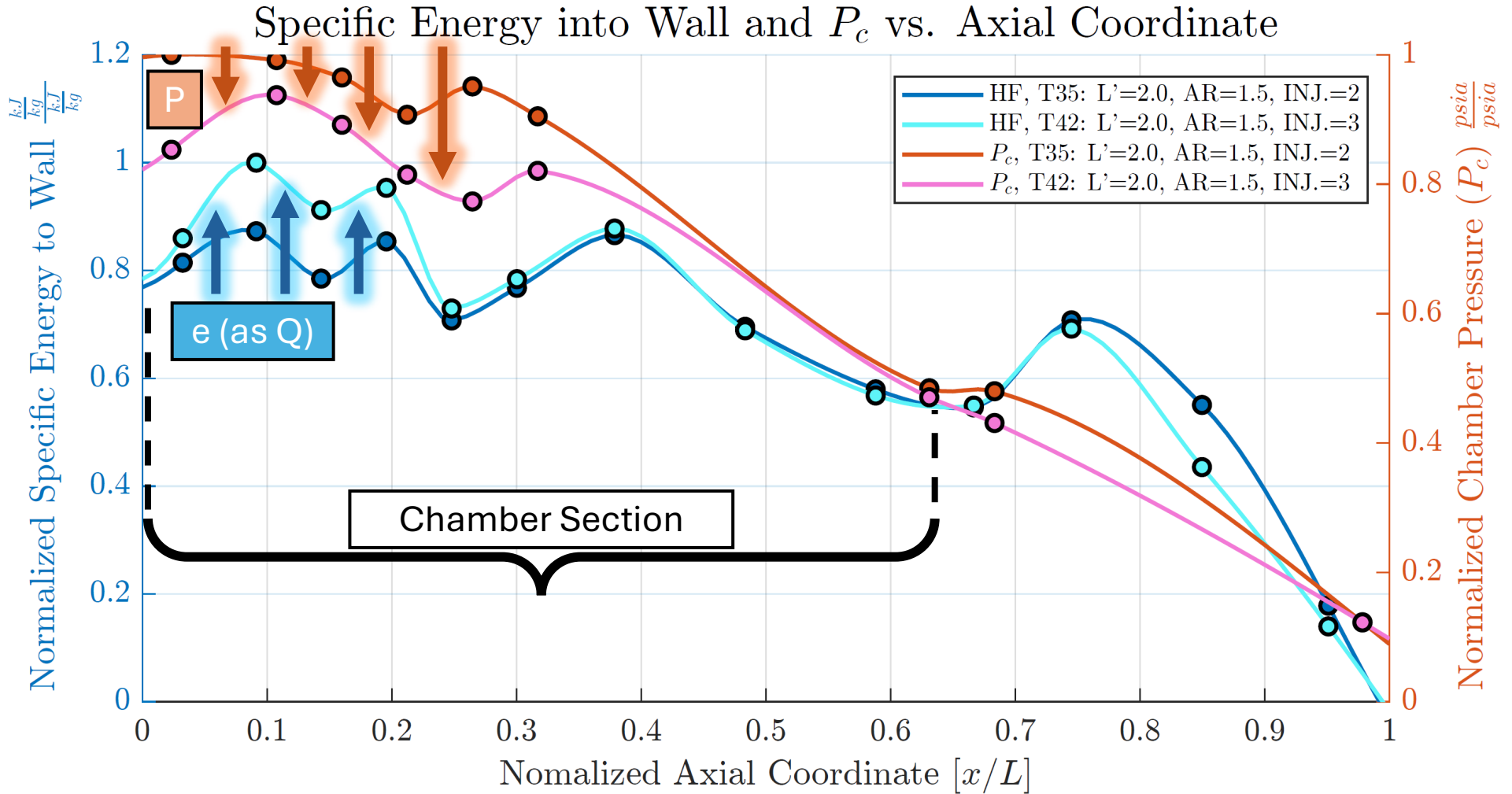
Raw Heat Flux Data



Specific Energy into Combustor Wall (Heat Flux/Local Mass Flux)

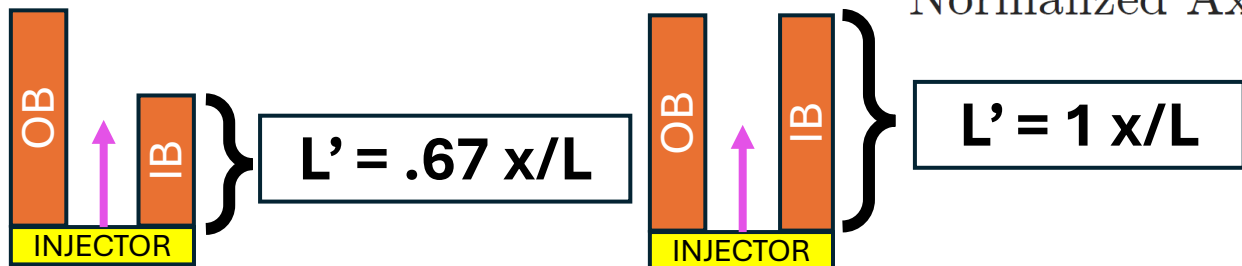
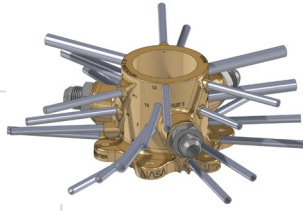
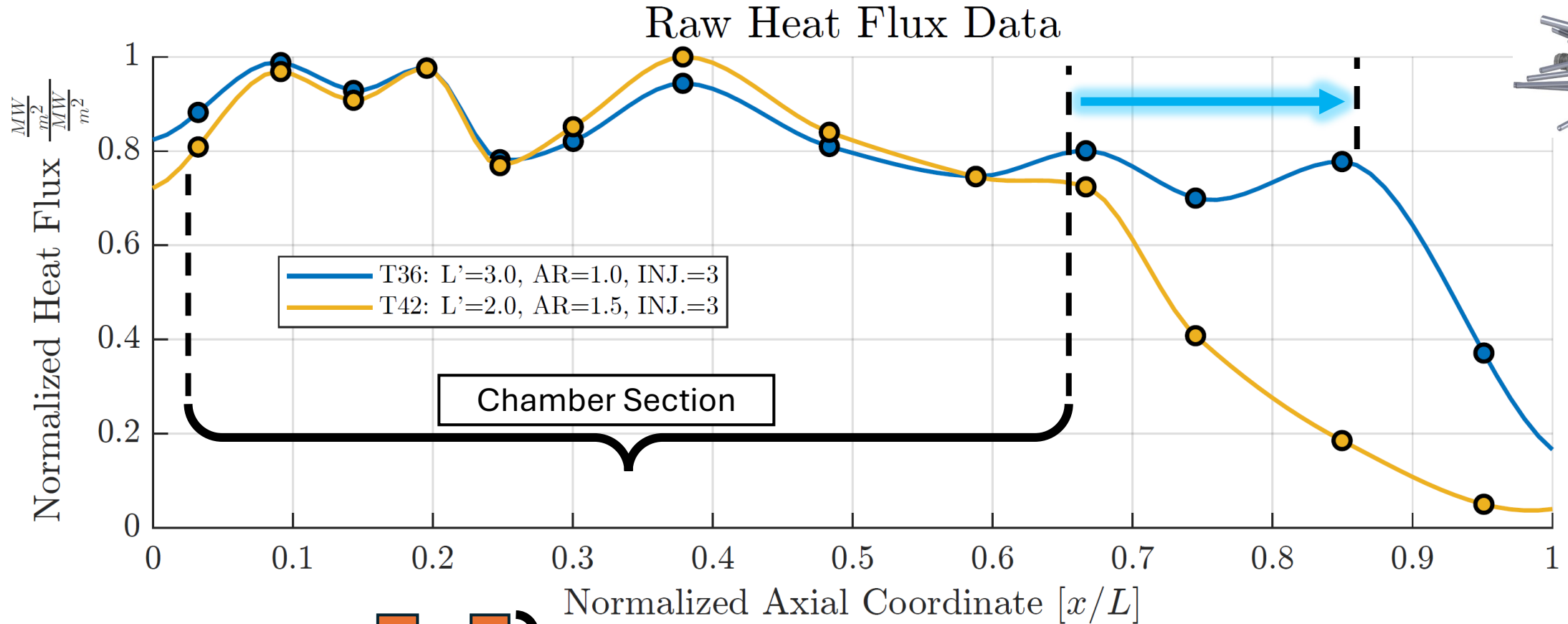


Injector Change – Specific Energy



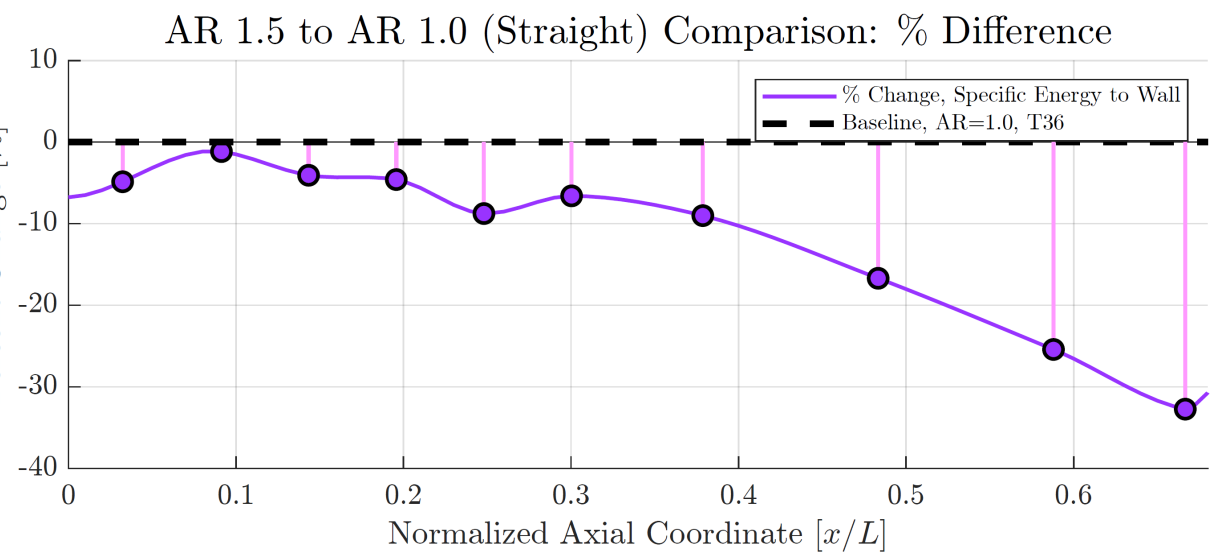
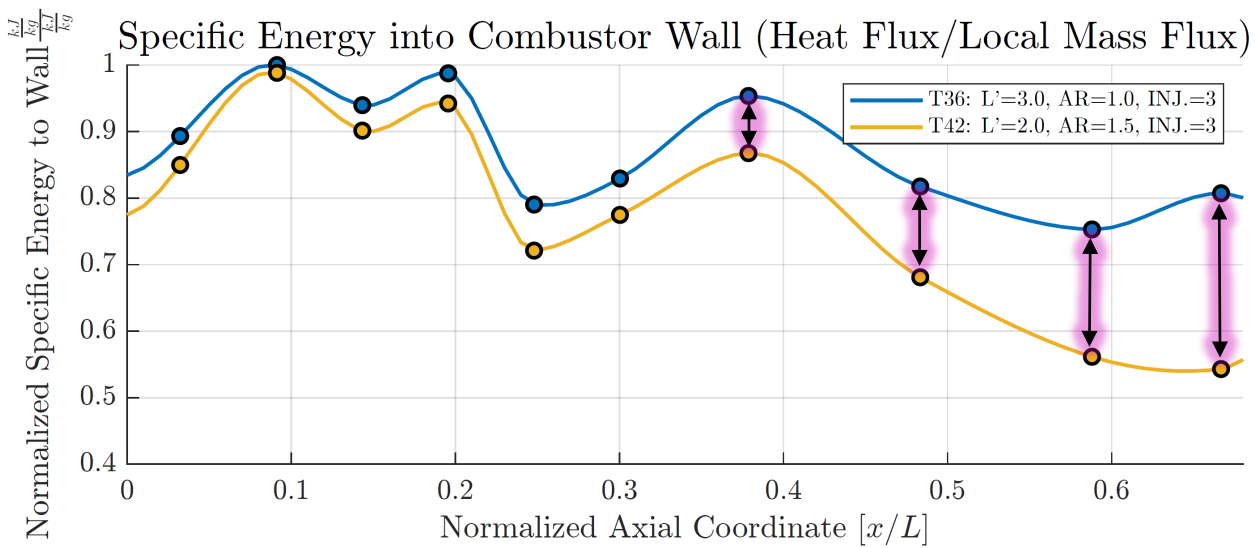
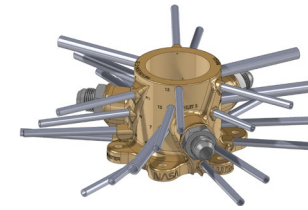
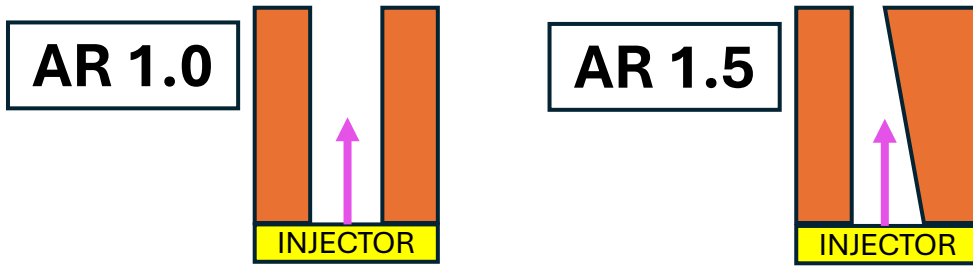
Lower P_c , higher e (as Q) to wall

Inner Body Length (L') Change



$$\Sigma \dot{Q}_3'' > \Sigma \dot{Q}_2''$$

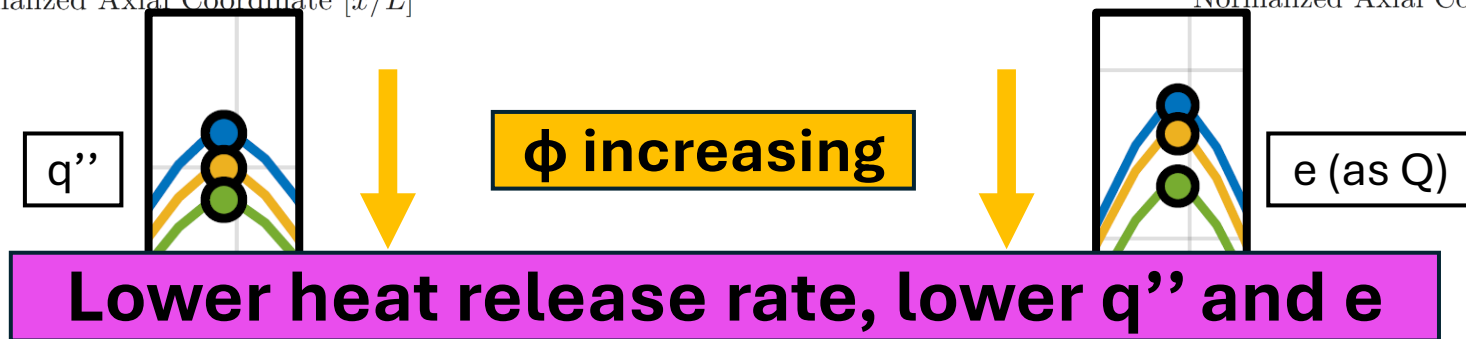
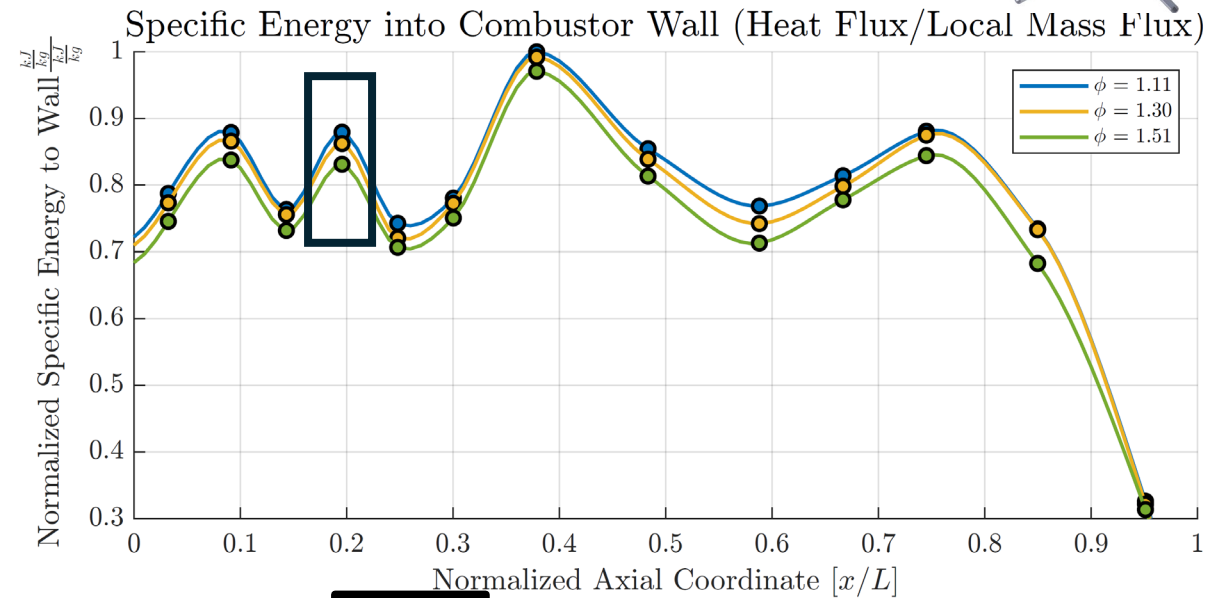
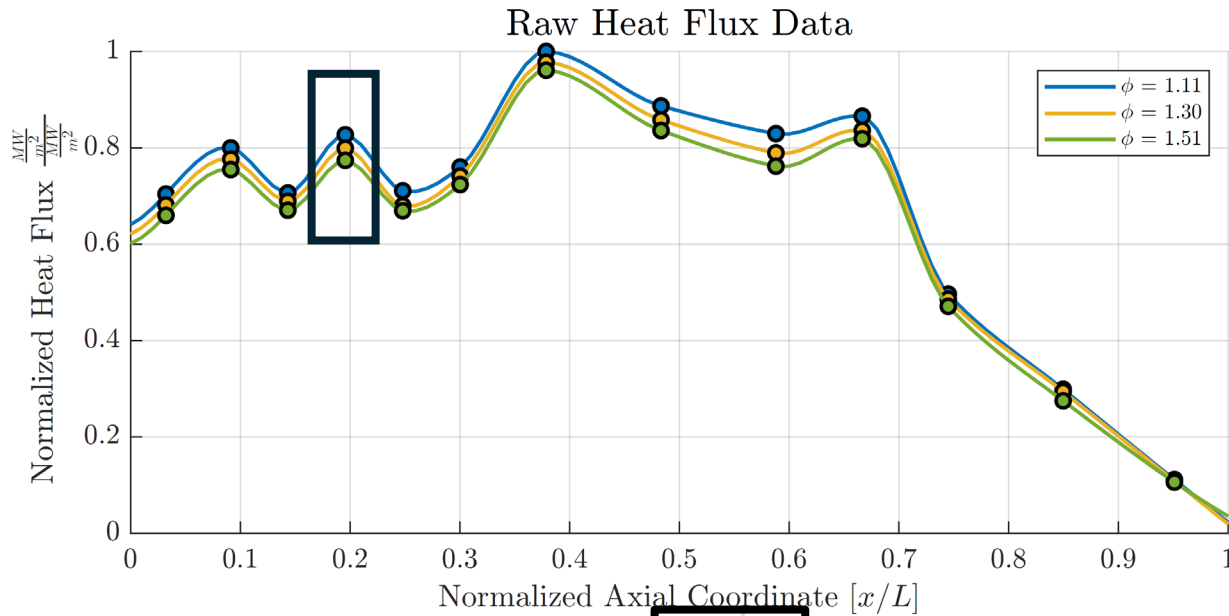
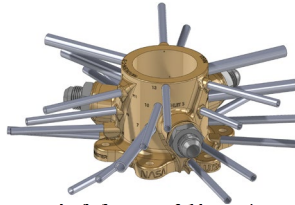
AR Change (1.0 to 1.5)



Increase AR for (given inj. mass flux), reduced e (as Q) to wall

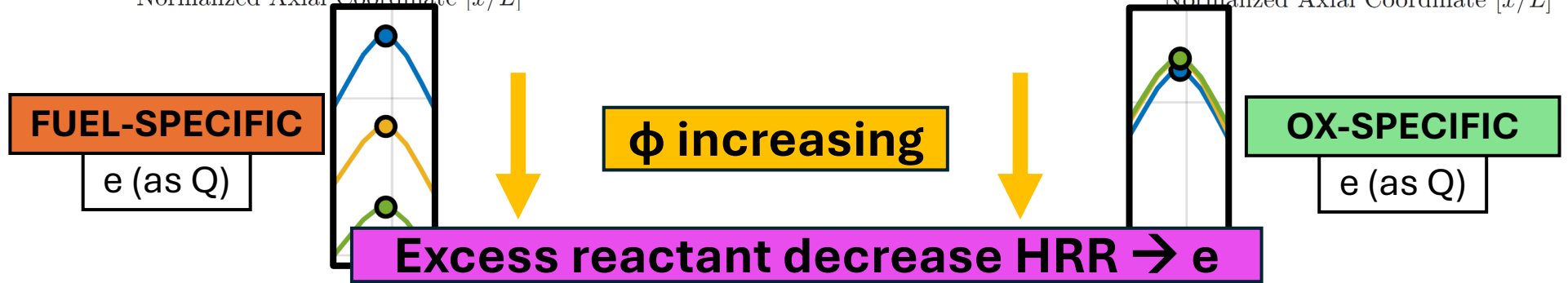
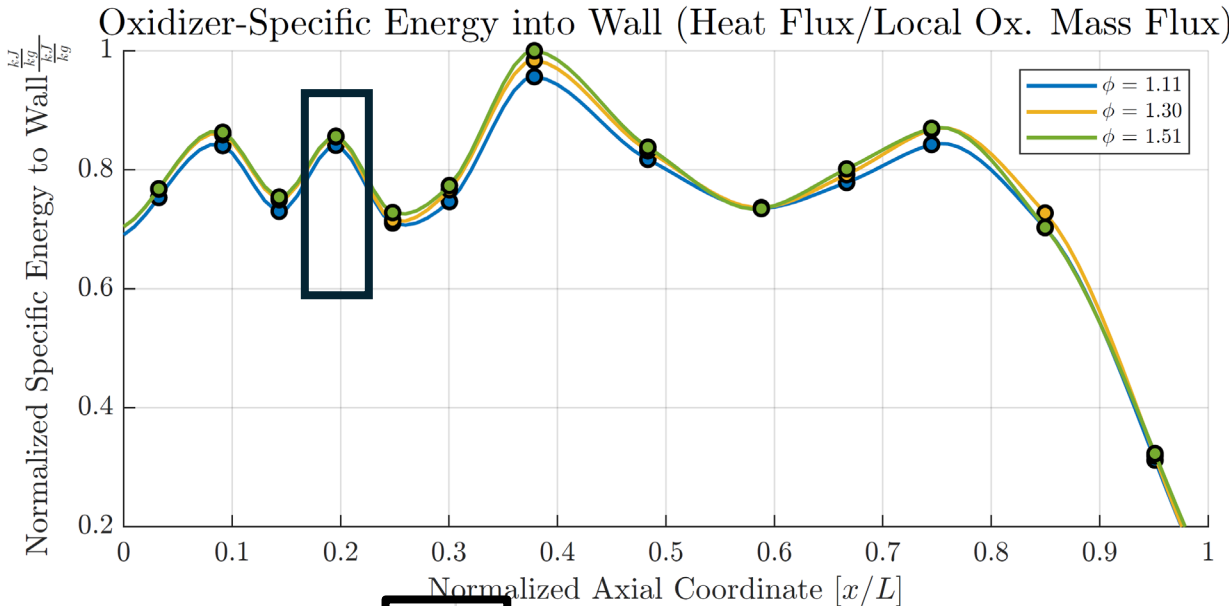
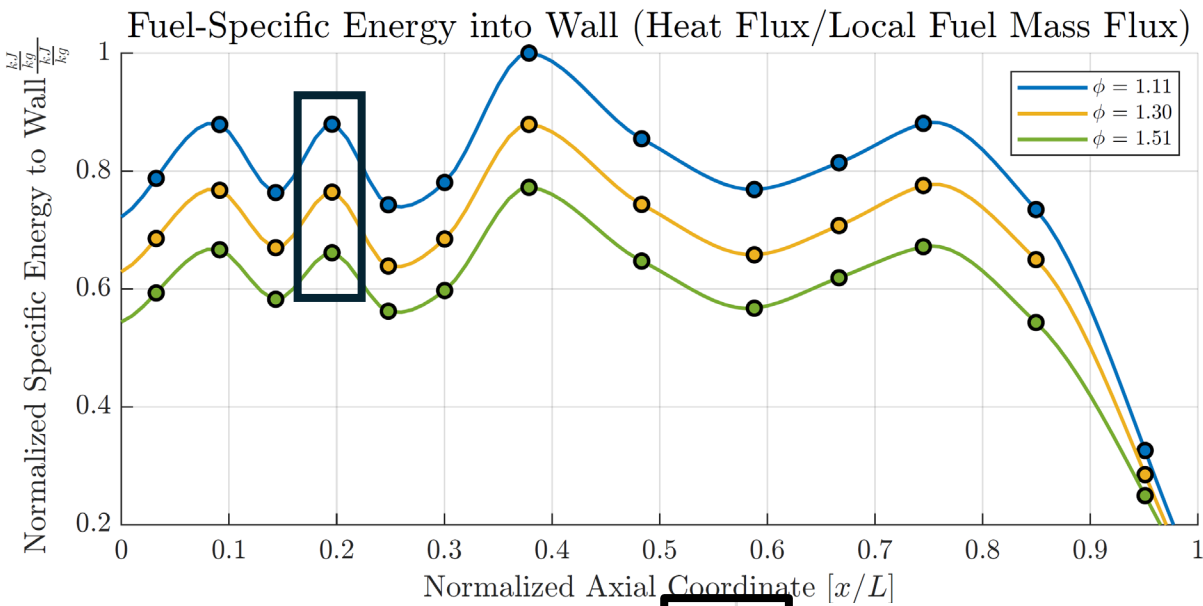
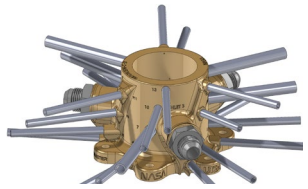
Equivalence Ratio - Overall

$\phi > 1$



Equivalence Ratio – Fuel/Ox-Specific

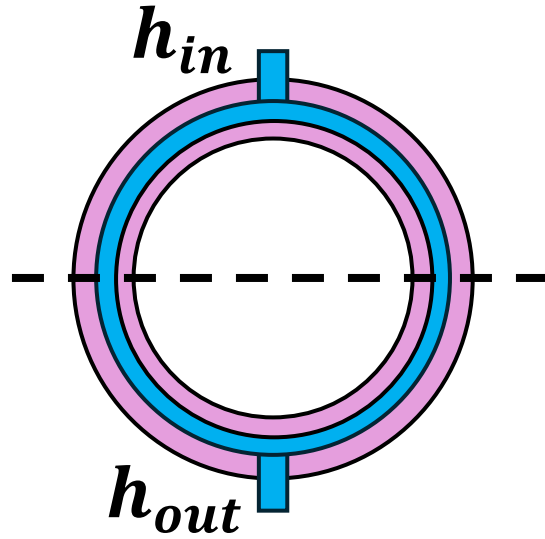
$\phi > 1$



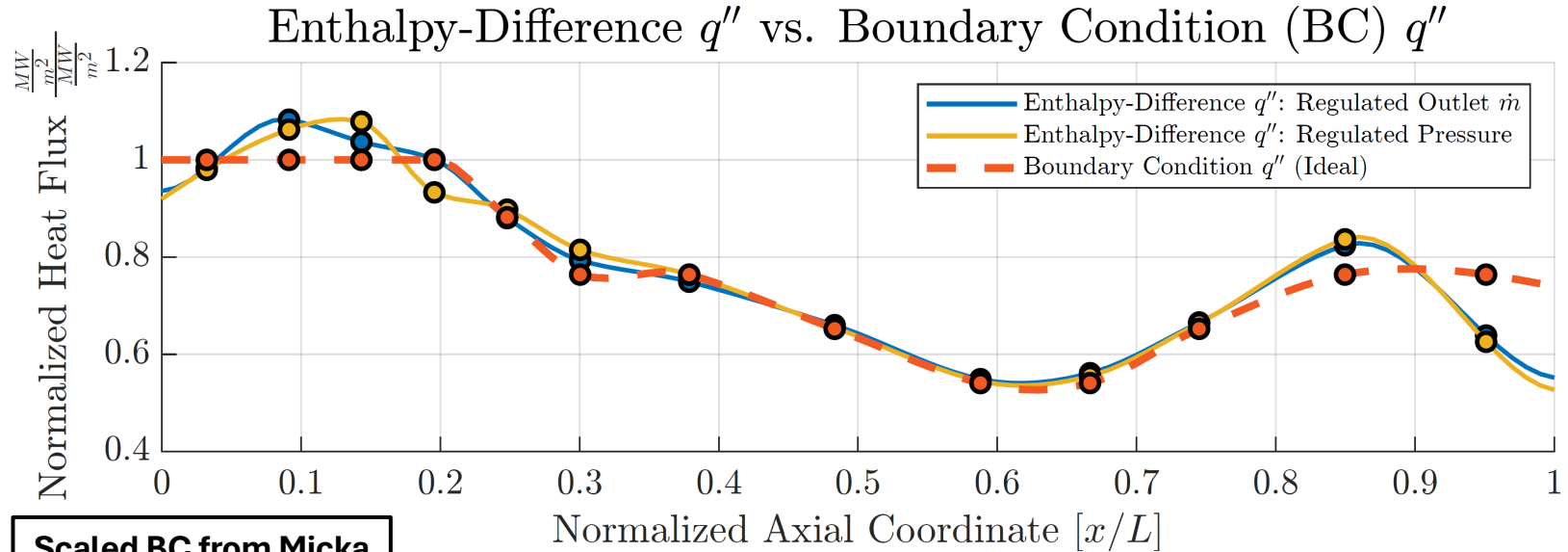


Data Transformation

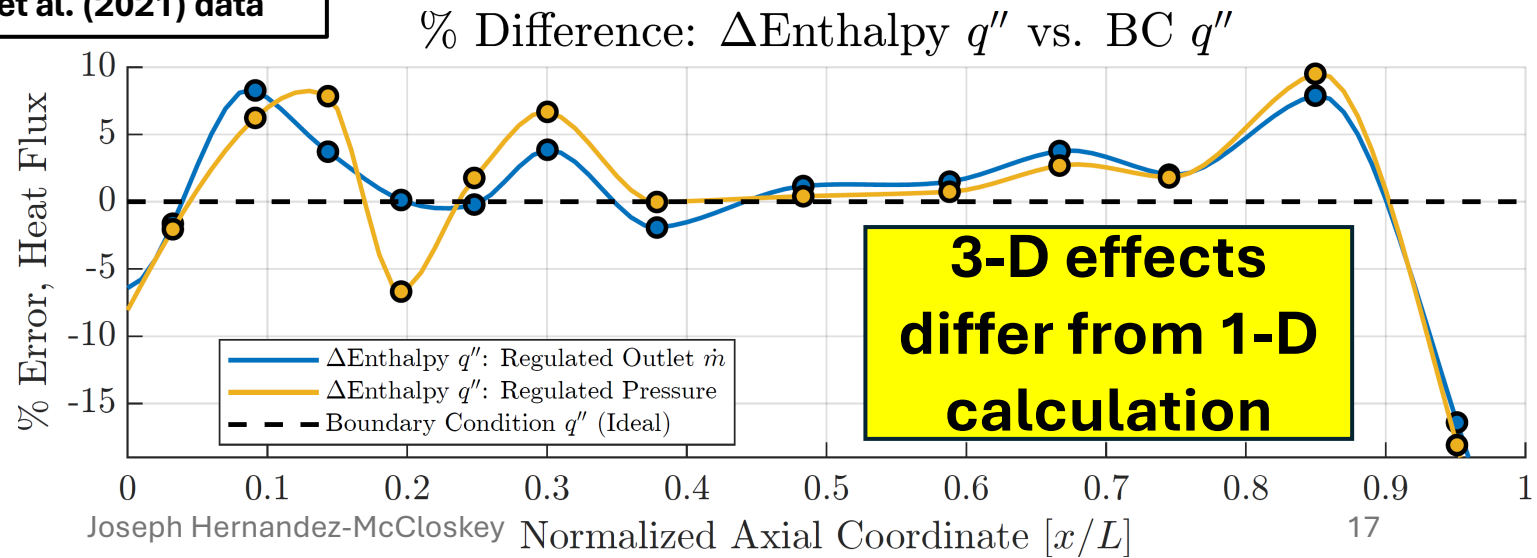
3-D Effects, Conjugate Heat Transfer (CHT)



$$q''_{\Delta enthalpy} = \frac{\dot{m}\Delta h}{A}$$



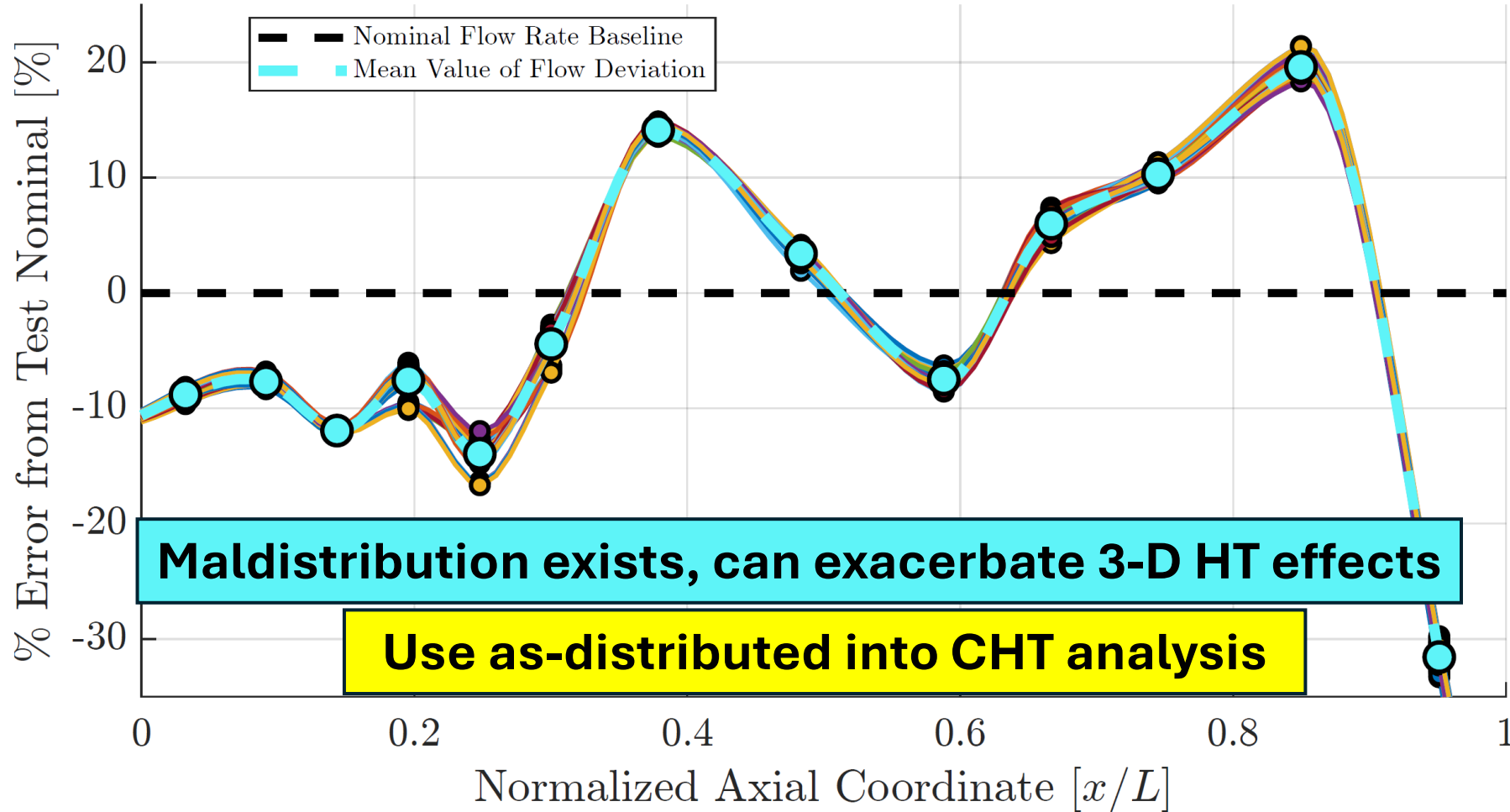
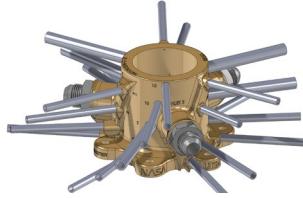
Scaled BC from Micka et al. (2021) data



3-D effects differ from 1-D calculation

Coolant Maldistribution

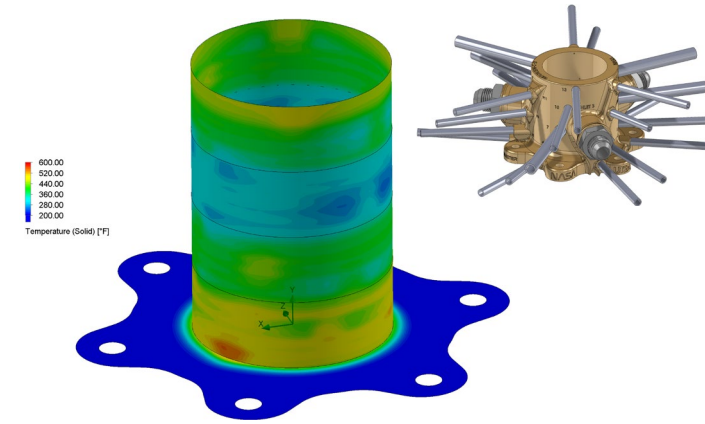
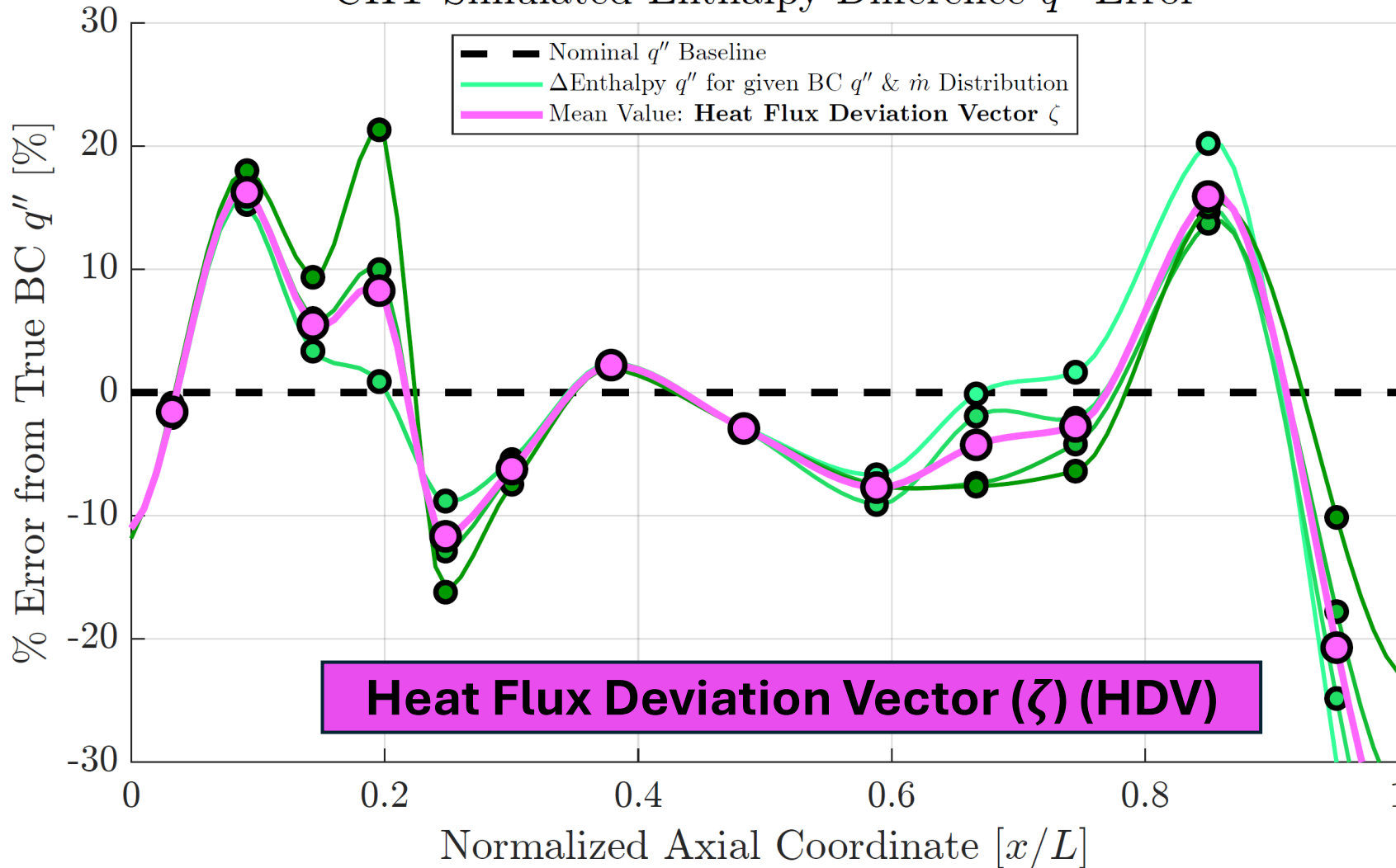
Coolant Mass Flow Rate Maldistribution (44 tests)



Coolant Mass Flow Deviation	
Station	Mean % Error
1	-8.82%
2	-7.67%
3	-11.93%
4	-7.56%
5	-13.94%
6	-4.42%
7	14.12%
8	3.42%
9	-7.48%
10	6.01%
11	10.30%
12	19.59%
13	-31.56%

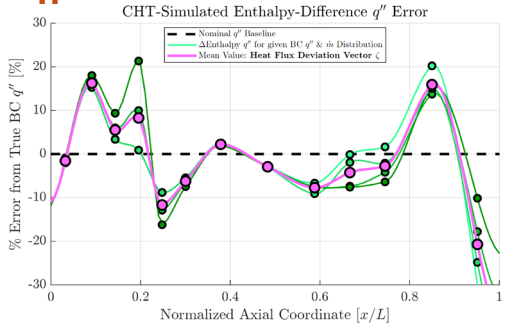
3-D Effects with Coolant Dist., CHT

CHT-Simulated Enthalpy-Difference q'' Error



Heat Flux Deviation Vector (ζ)	
Station	Mean % Error
1	-1.58%
2	16.24%
3	5.51%
4	8.26%
5	-11.69%
6	-6.23%
7	2.21%
8	-2.93%
9	-7.72%
10	-4.26%
11	-2.76%
12	15.90%
13	-20.72%

Data Transformation



→ ζ (HDV)

$$H_{cal} = \frac{1}{\zeta}$$

Calorimeter transfer function

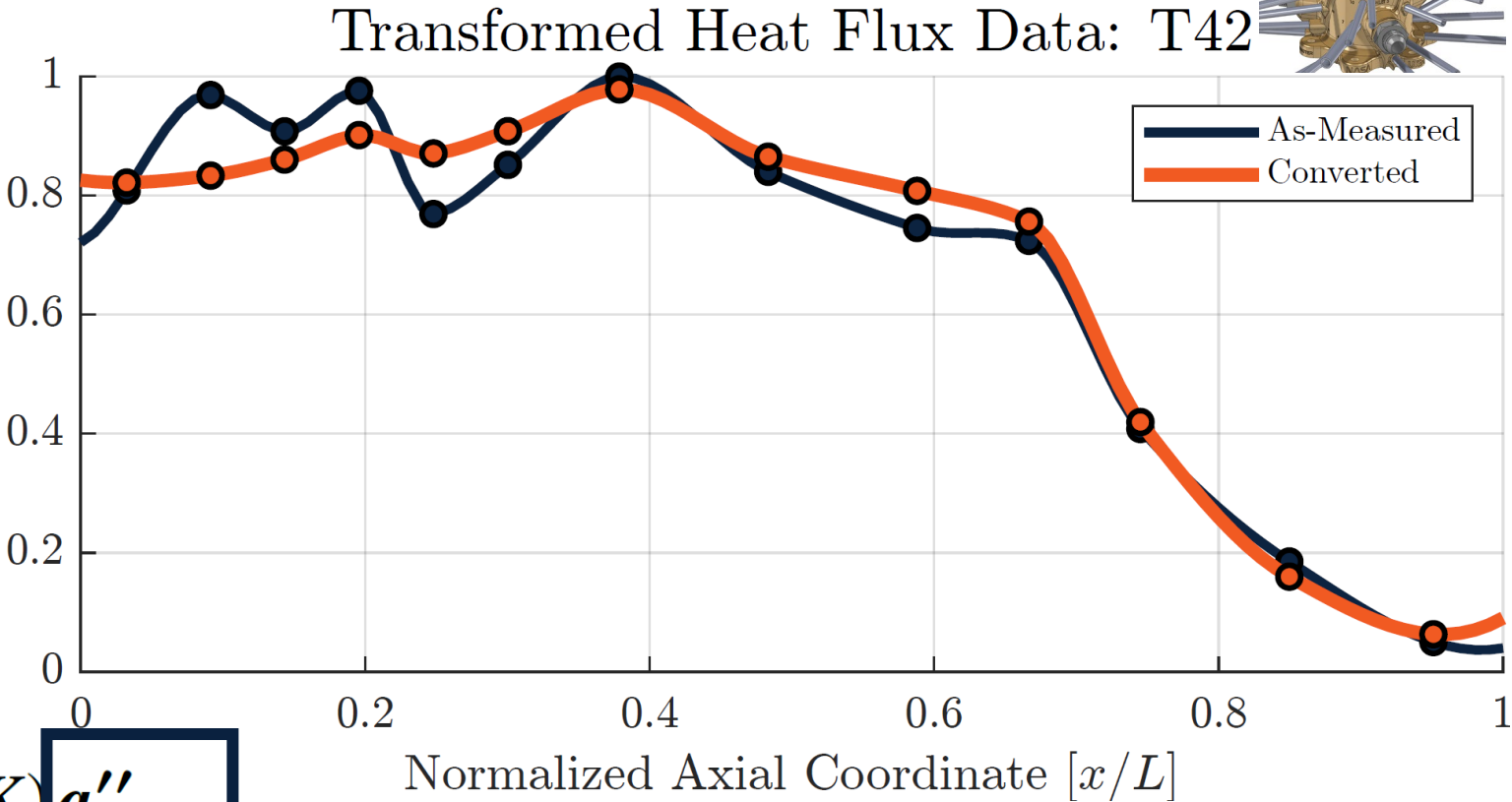
$$K = \left[1 - \frac{q''_{theo}}{q''_{meas}} \right]$$

$$q''_{theo} = (H_{cal} \cdot K) q''_{meas}$$

Corrected

Measured

Normalized Heat Flux $\frac{MW}{m^2} / \frac{MW}{m^2}$





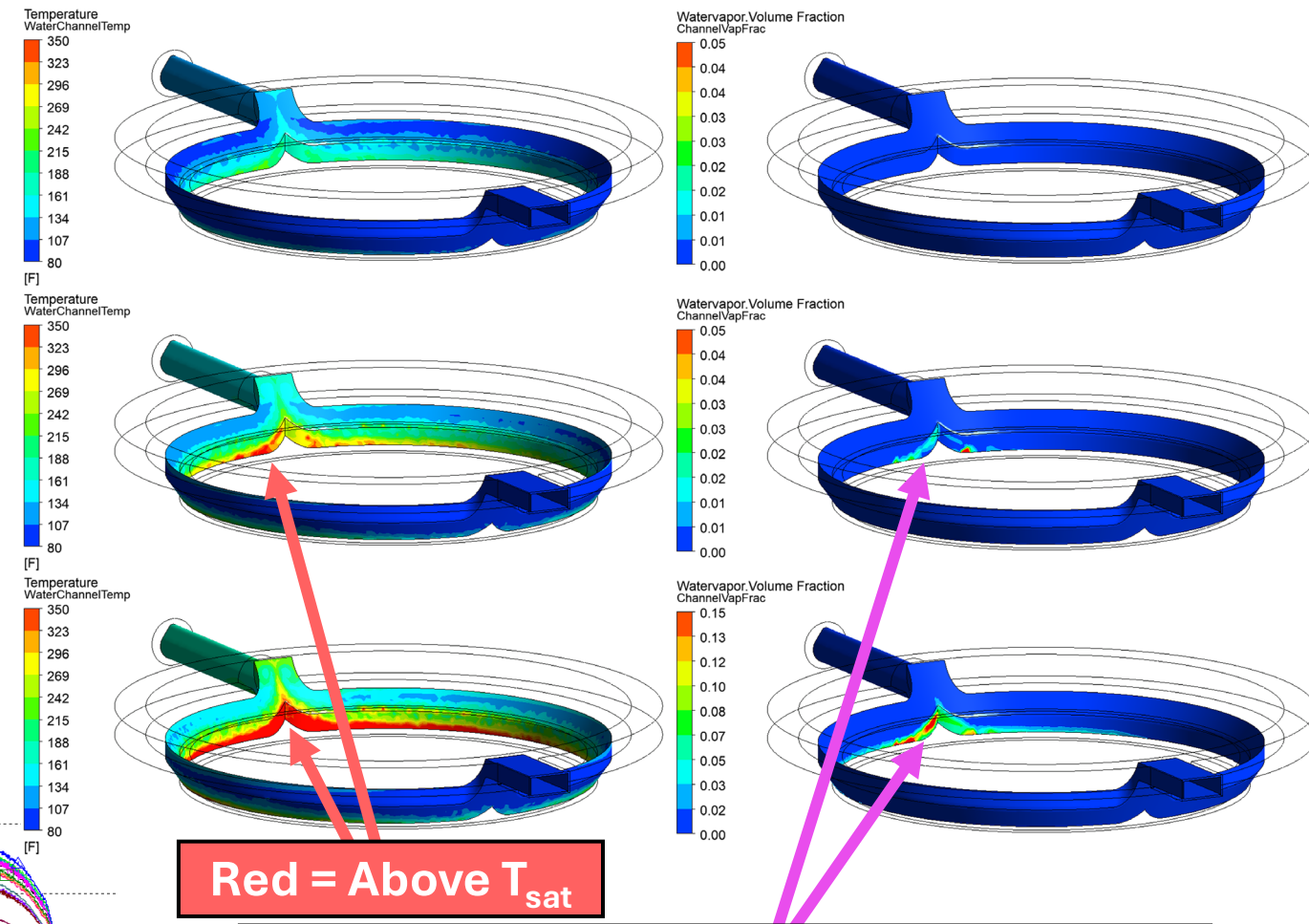
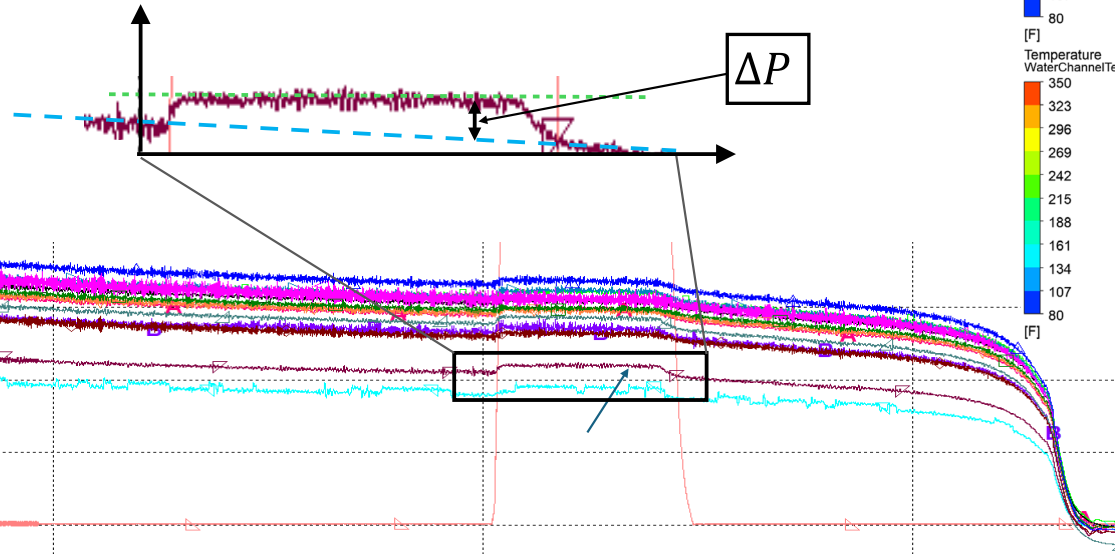
Boiling Analysis

Boiling Investigation and CHT Analysis

- Exit orifices larger than design

Coolant pressure < design
→ Saturation Temp. < design

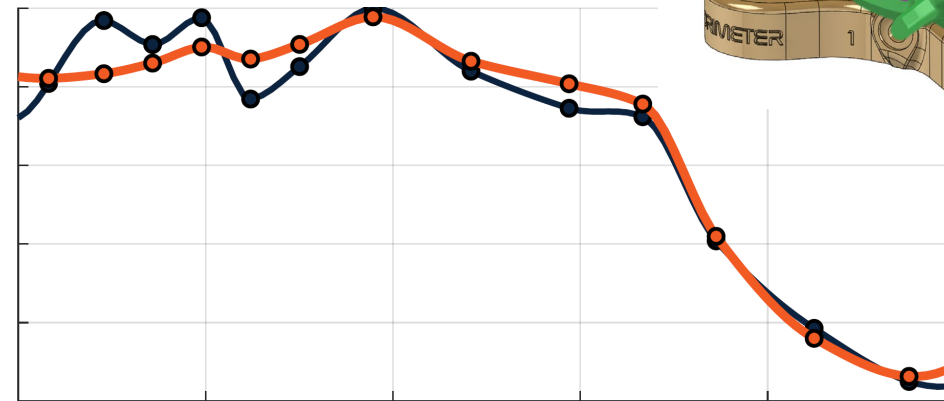
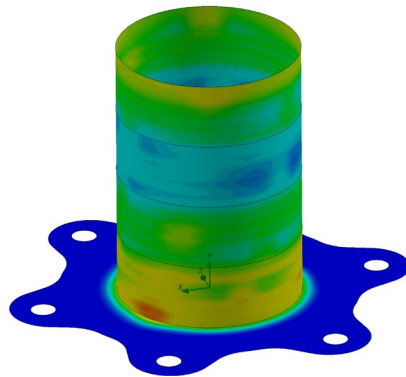
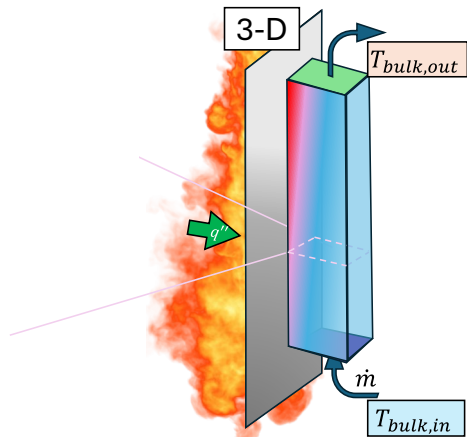
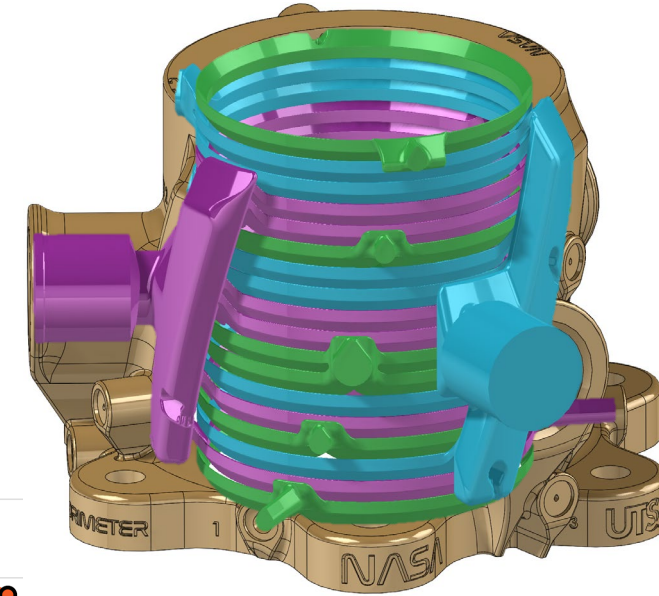
Potential vapor generation



Vapor fraction present in arbitrary medium/high heat flux cases

Summary/Future Work

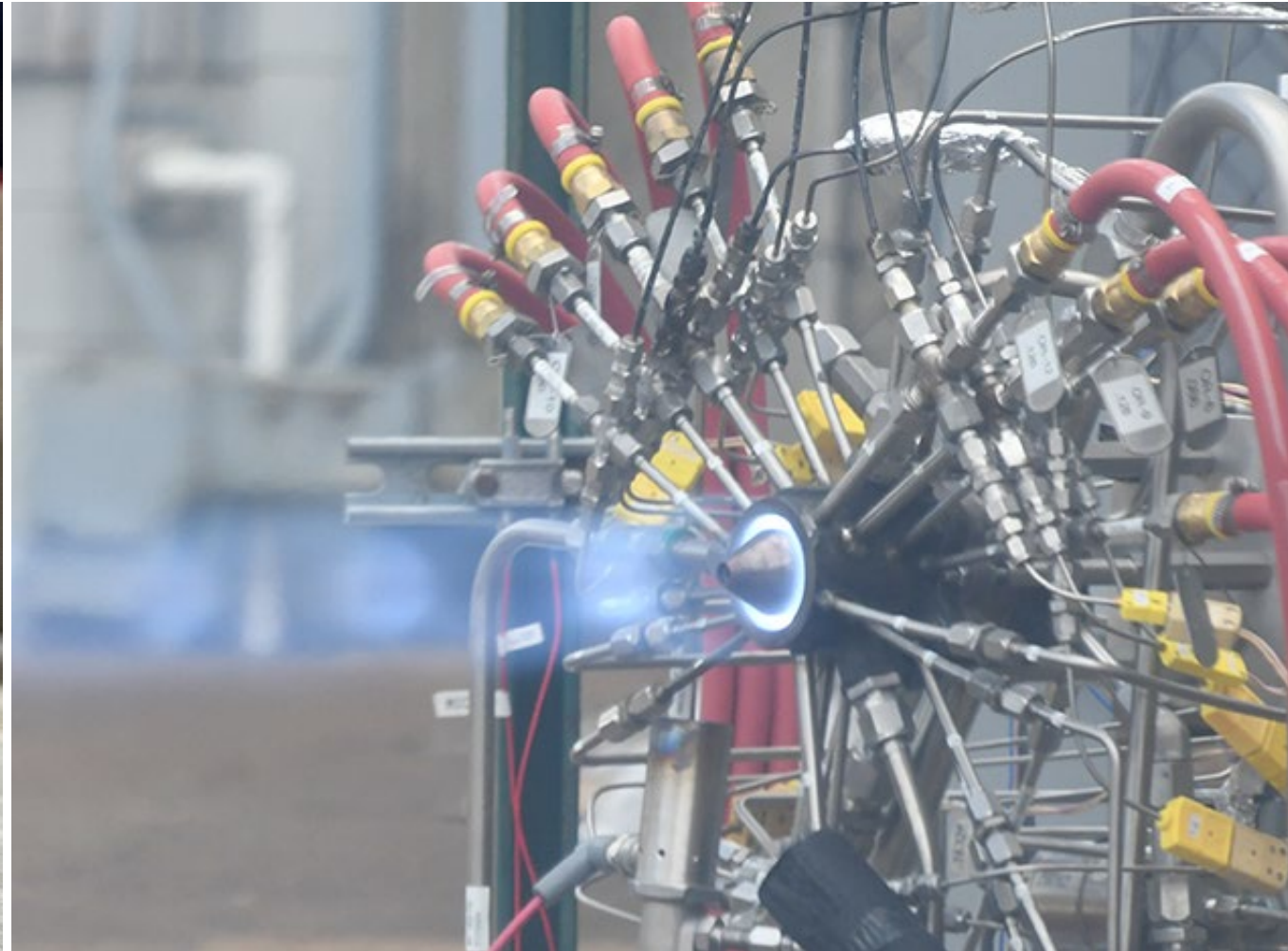
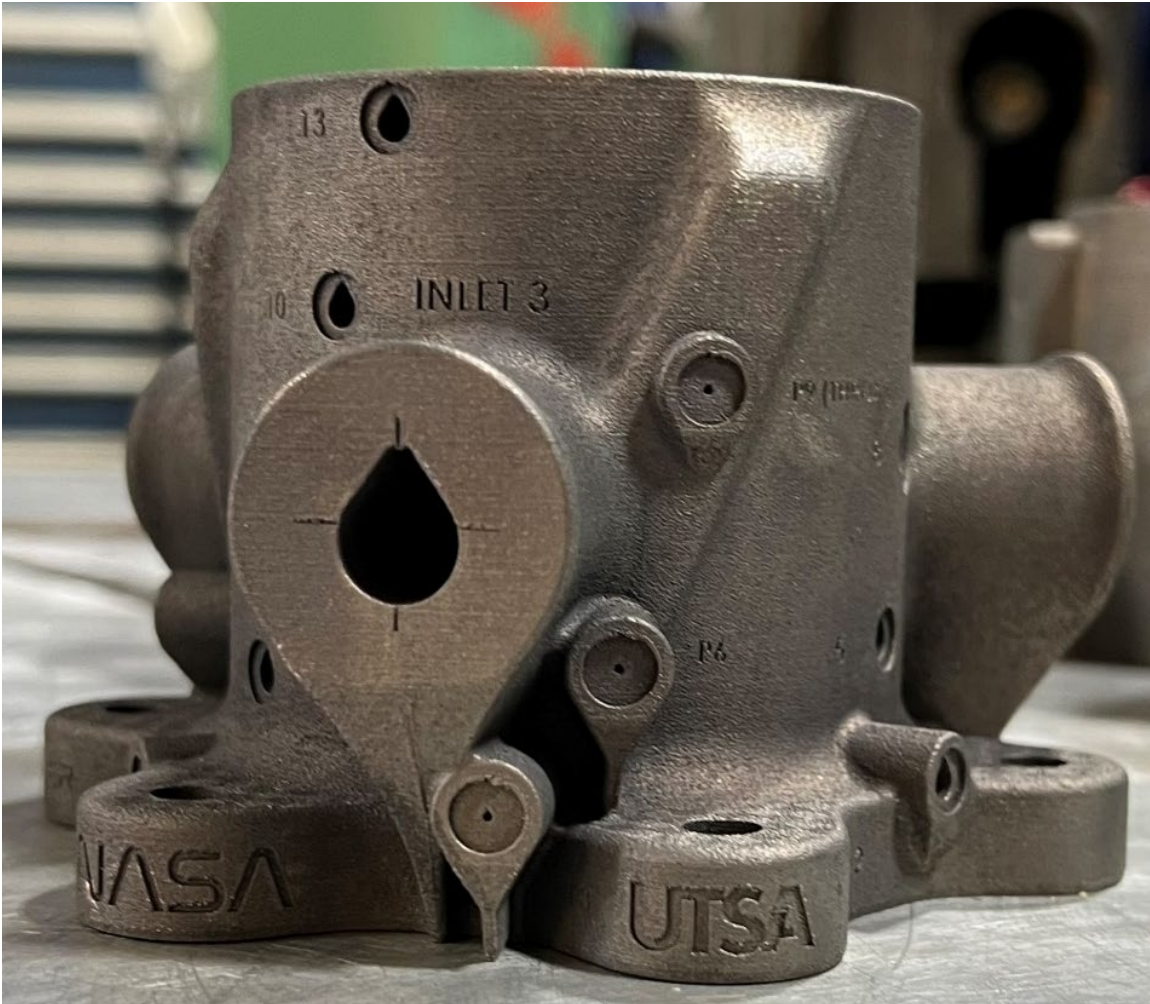
- Designed/manf./tested AM calorimeter hardware
- Analyzed first-order local heat flux/energy trends
- Developed calorimeter transfer function (CTF)
 - Mitigate 3-D heat transfer effects/coolant maldistribution
- Investigated presence of vapor



- Modify orifices for higher back pressure
- Further investigate boiling heat transfer

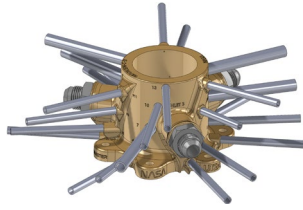
SIGNIFICANT NEED FOR MORE DATA!

Questions?

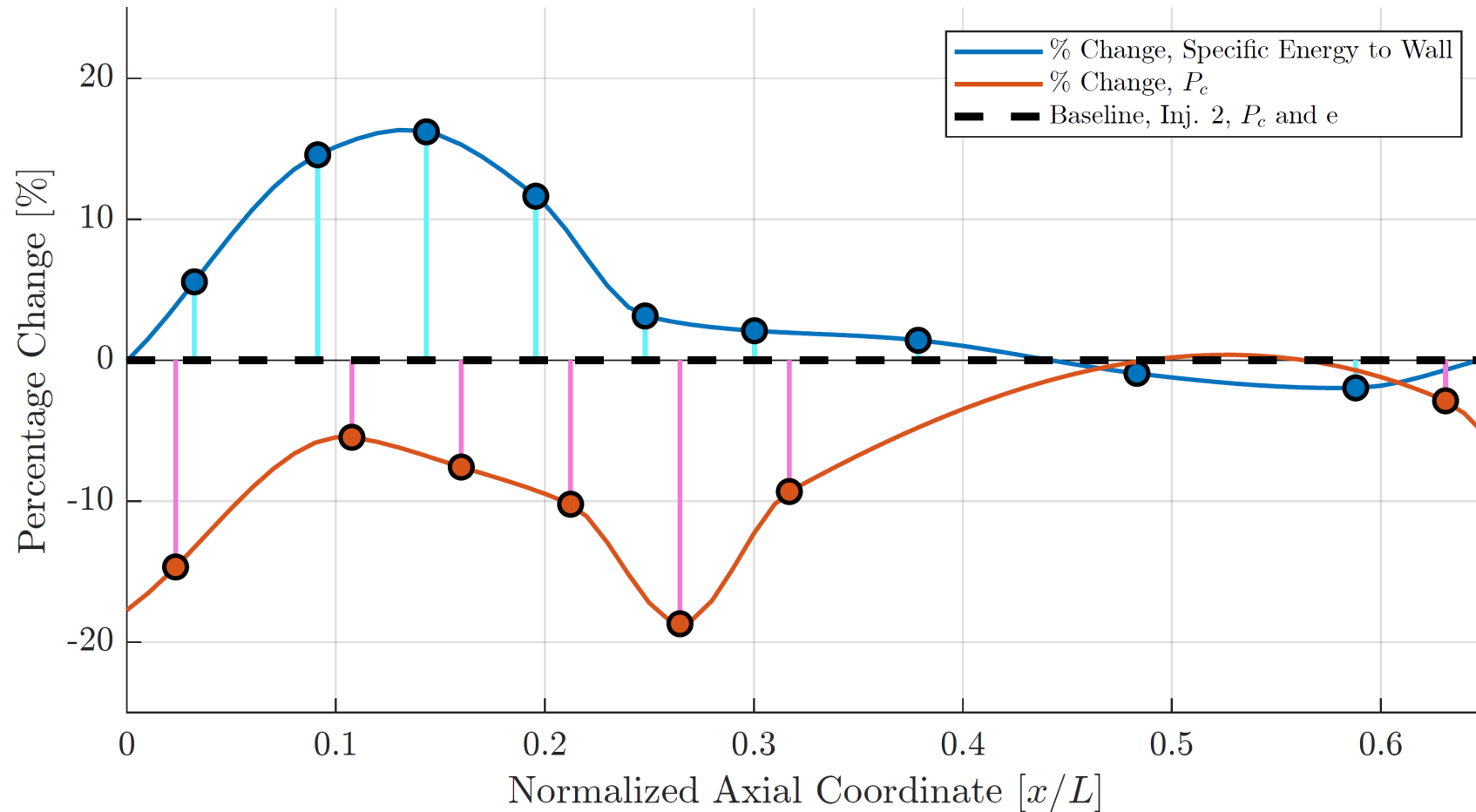


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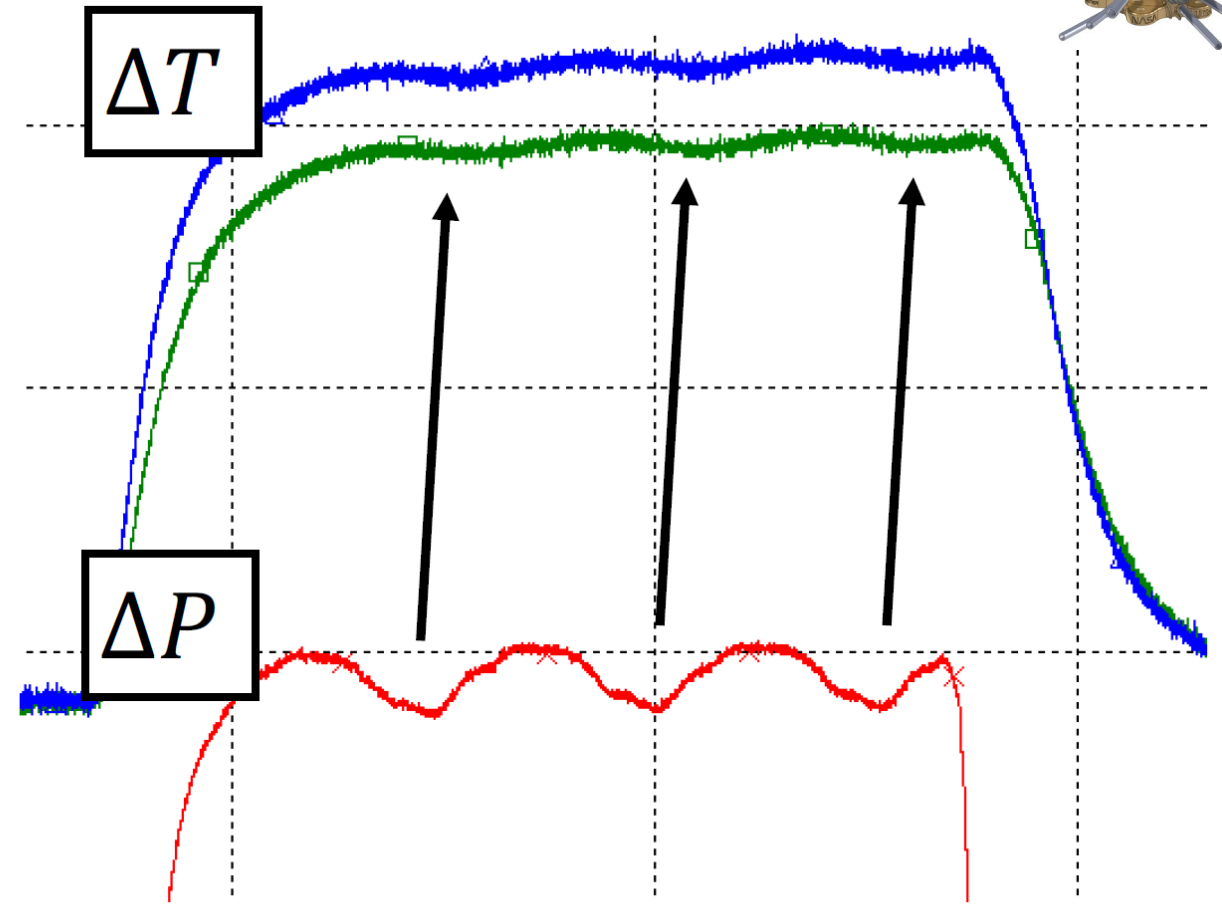
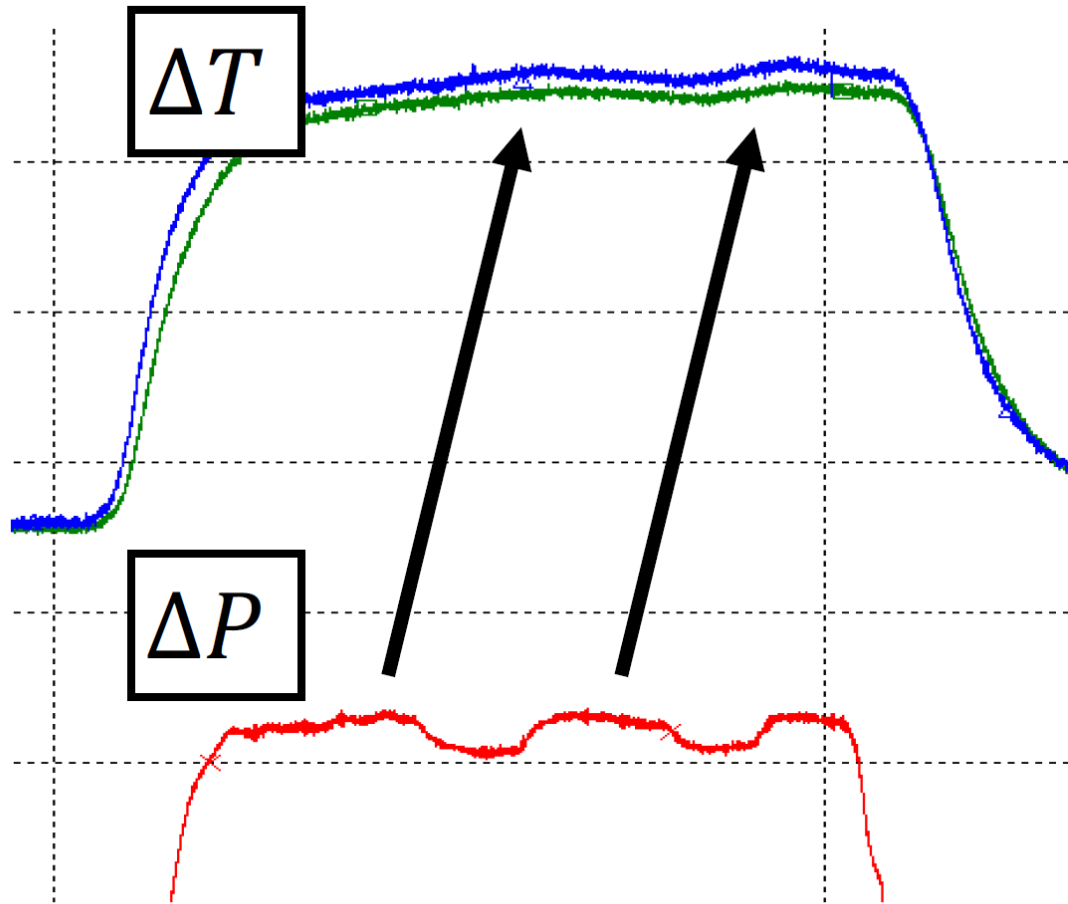
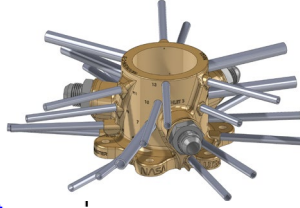
Injector Change – Comparison



Inj. 3 to Inj. 2 Comparison: % Difference (vs. Inj. 2 Value)

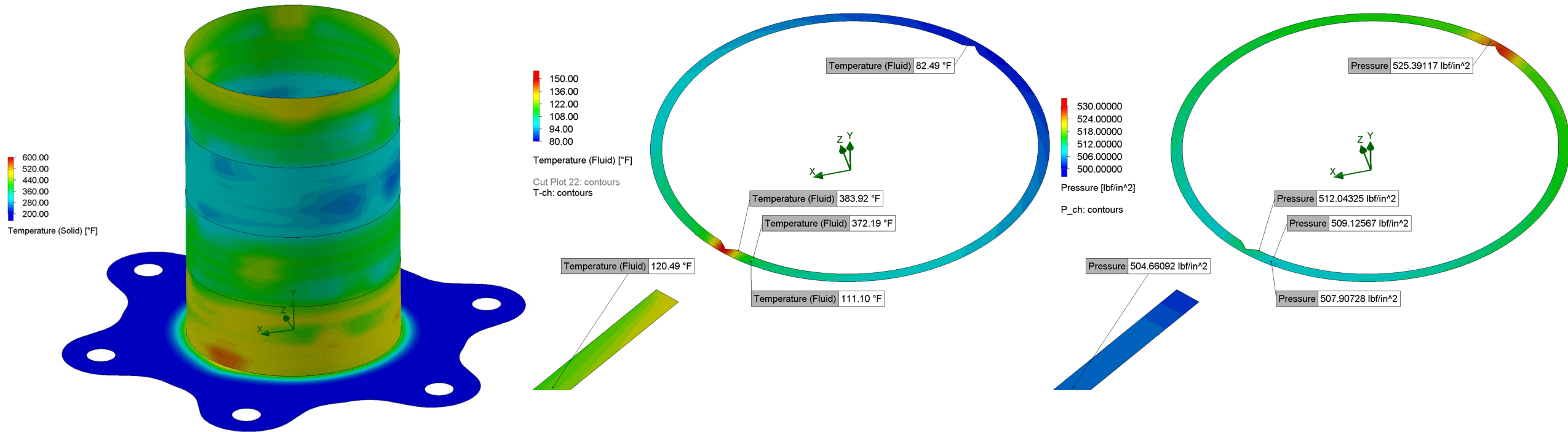


Wave Mode Shift - Thermocouple Data

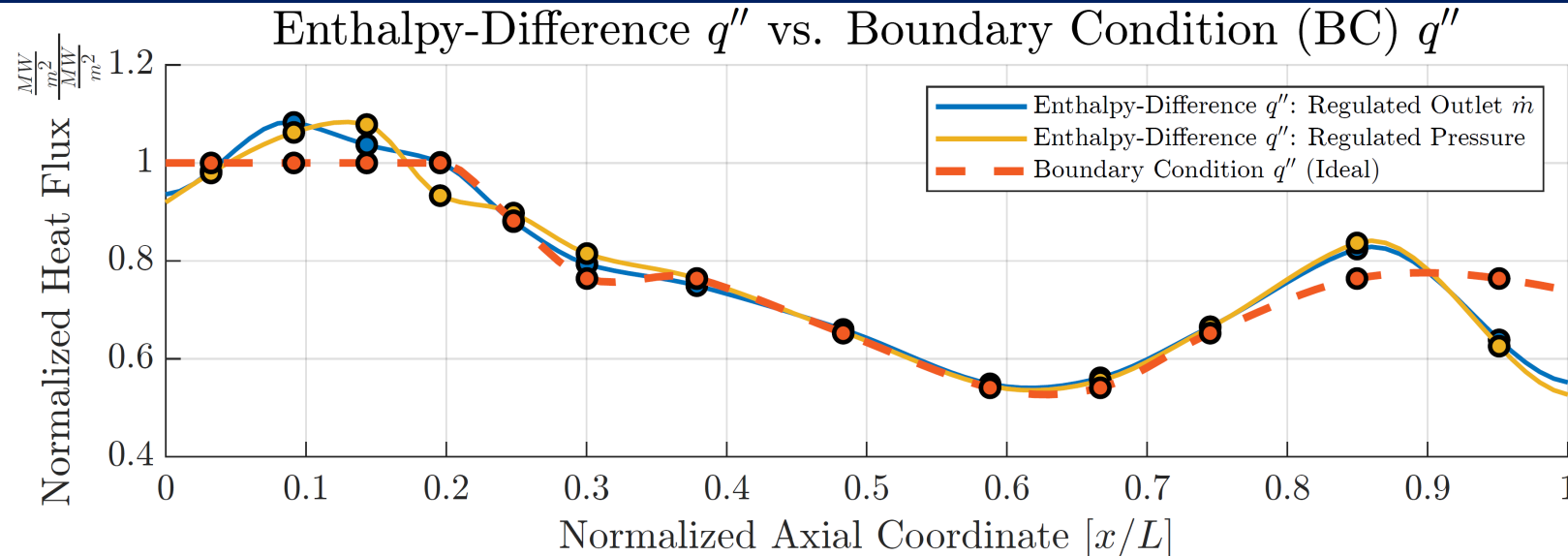


Design Simulations – 1

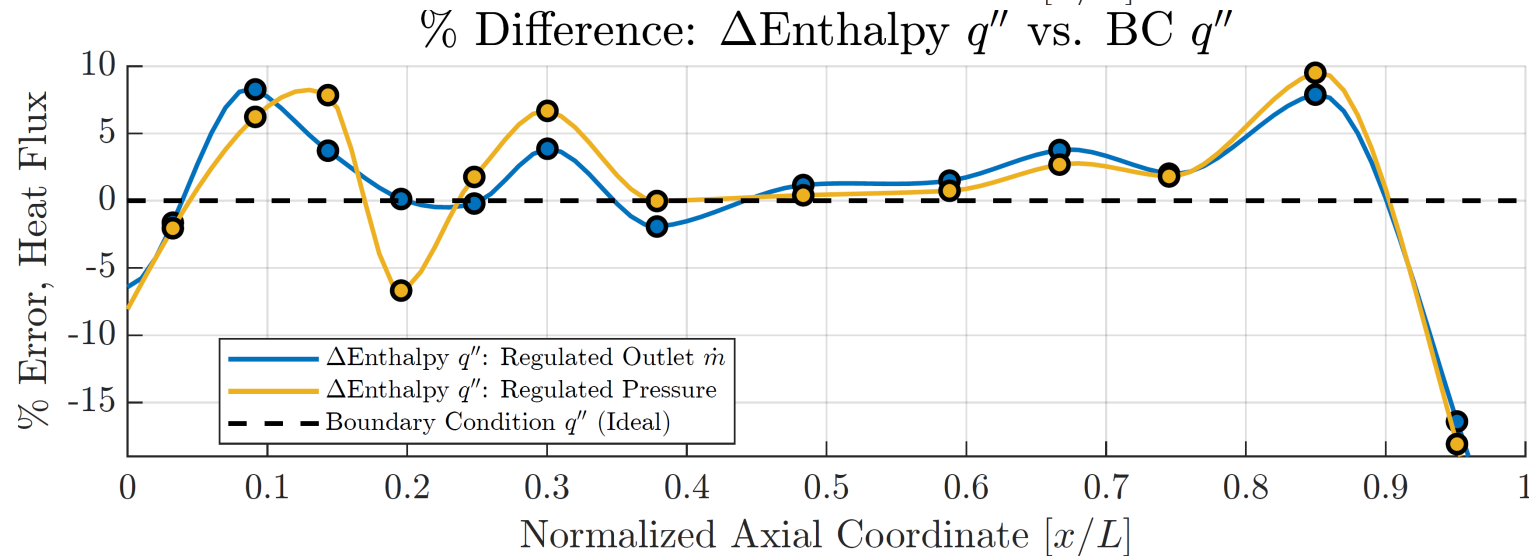
- Conjugate heat transfer sims using prescribed boundary conditions from scaled Micka et al. (2021) data



Design Simulations – 2

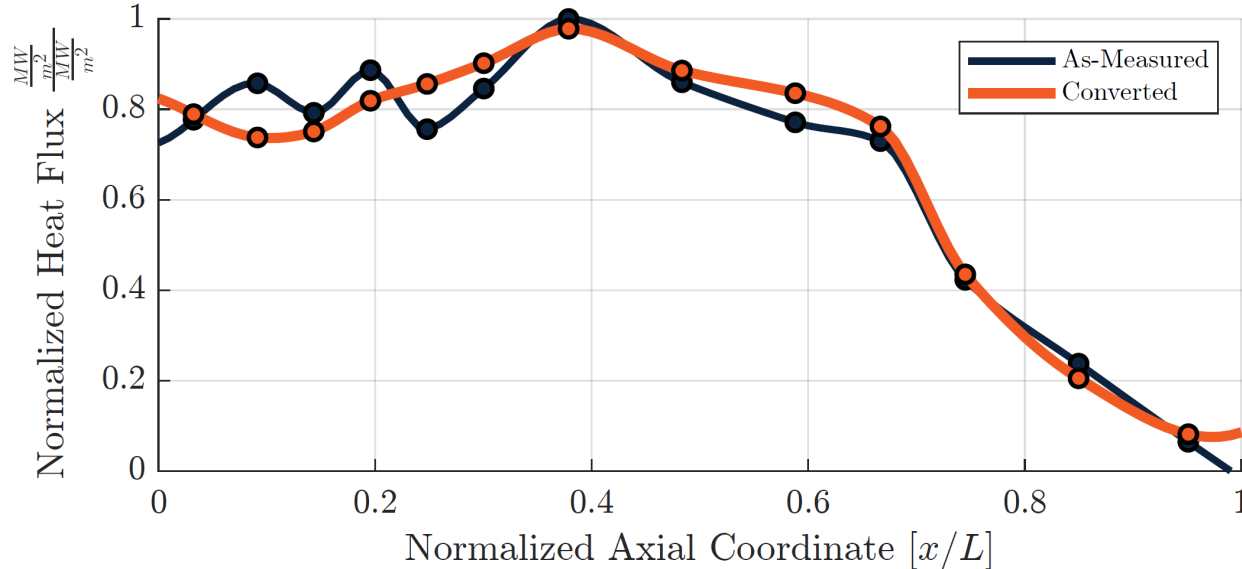


Prescribed boundary conditions from scaled Micka et al. (2021) data

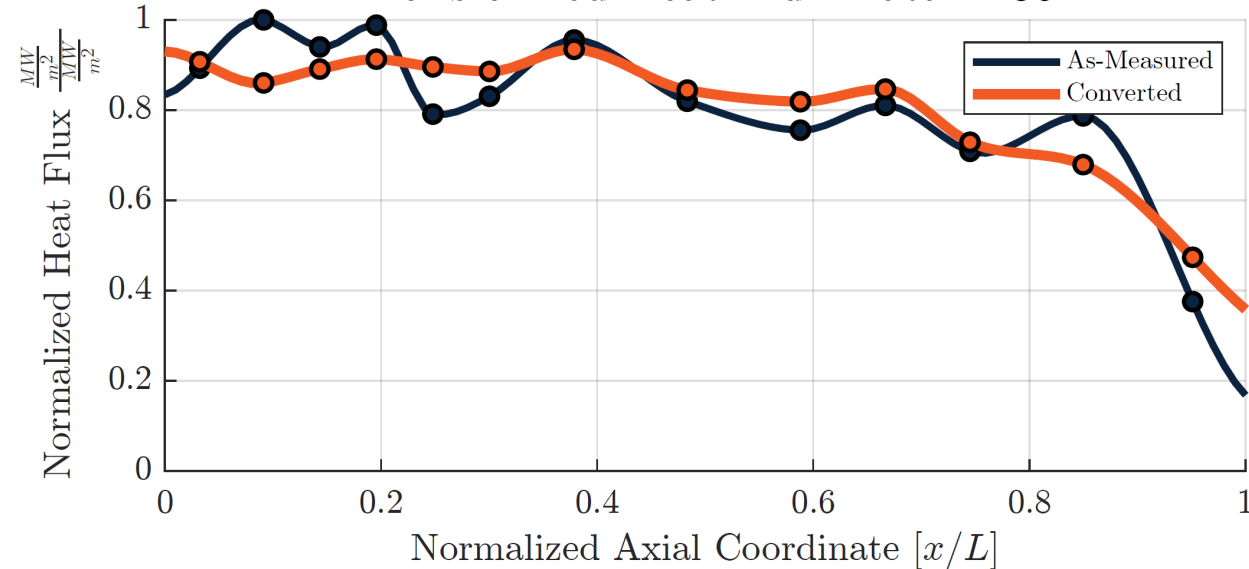


Additional Transformed Data

Transformed Heat Flux Data: T35



Transformed Heat Flux Data: T36



$$H_{cal} = \frac{1}{\zeta} \quad K = \left[1 - \frac{q''_{theo}}{q''_{meas}} \right]$$

$$q''_{theo} = (H_{cal} \cdot K) q''_{meas}$$

Can also be expressed as:

$$(q''_{theo} \cdot \zeta) + q''_{theo} = q''_{meas}$$