



# Heat Transfer Experiments of a 1st Stage Blade Cascade for Supercritical CO<sub>2</sub> Oxy-Combustion Turbine Application

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# Acknowledgement

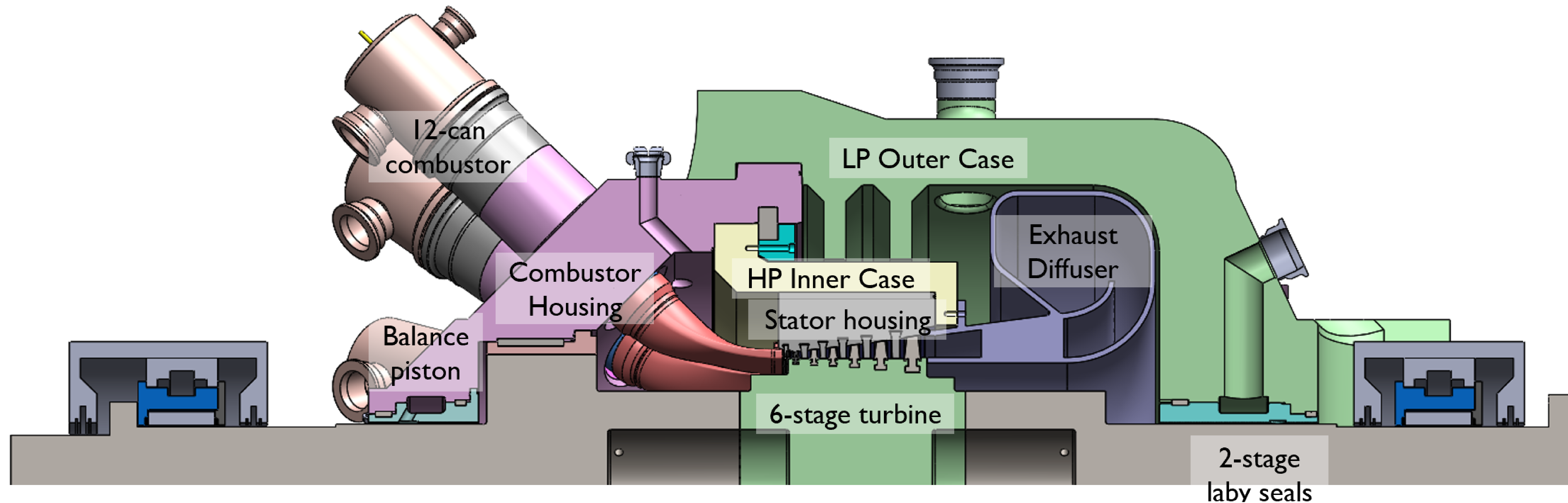
- Work completed under the project, “Development of Coal Syngas Oxy-Combustion Turbine for Use in Advanced sCO<sub>2</sub> Power Cycles”, sponsored by the U.S. Department of Energy (FE-0031929).

# Introduction – Direct Fired sCO<sub>2</sub> Cycles

- A utility-scale, direct-fired sCO<sub>2</sub> turbine was designed for operation in the Allam-Fetvedt cycle, utilizing coal-derived syngas and the ability to co-fire with natural gas. Advantages:
  - Near zero emissions.
  - Compact machinery with the high fluid density.
- Targeted as a commercial product to be competitive with a natural gas combined cycle (NGCC) with carbon capture.

# Introduction – Turbine Details

- Scale of 300 MWe, TIT of 1150°C and inlet pressure of 305 bar.
- The predicted thermodynamic efficiency of the turbine is 92% with a per unit cost of \$96/kWe.

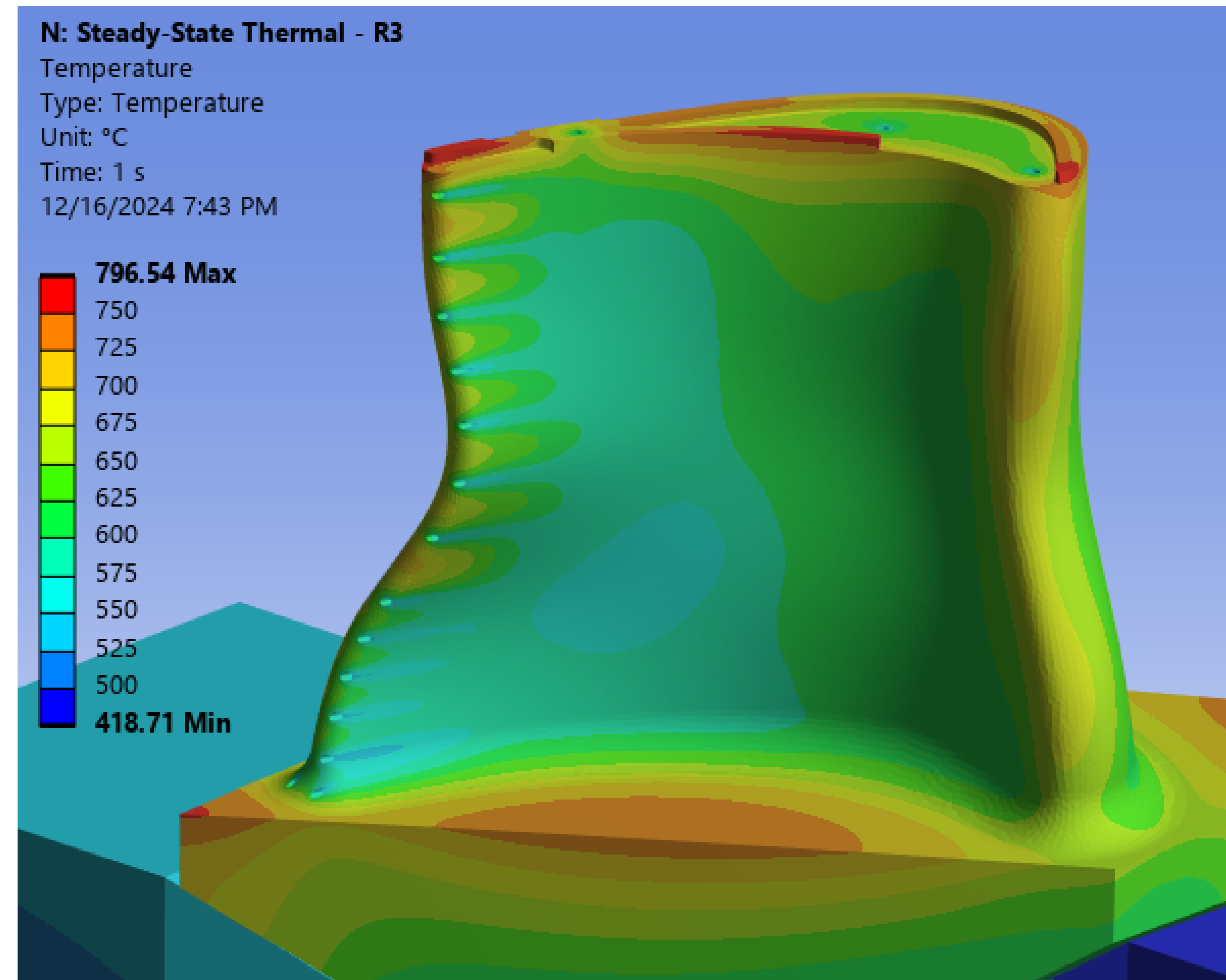


# Design of the 1<sup>st</sup> Stage Blade (S1B)

- CFD simulations predicted external heat loading characteristics (Purdue).
- Thermal cyclic TBC testing was conducted for Haynes 230 leading to a target TBC temperature of 1050°C.
- Testing was completed for internal cooling design features of LE impingement (UCF), mid-section ribbed serpentine channels (SwRI), and TE pin-fin array (UCF). Goal: Validation of existing Nusselt number correlations and enhancement ratios.

# Design of S1B – Thermal FE Analysis

- Source temperatures and HTC were imported from the URANS CFD simulations.
- Blade internal HTCs and source temperatures were input from a 1-D thermal and hydraulic network.



# Design of S1B

- Predicted metal temperatures determine blade life ratings.
  - H282 1000 hr. rupture strength @ 760°C: 262 MPa.
  - H282 1000 hr. rupture strength @ 871°C: 83 MPa.
- Need to understand the uncertainties inherent in the temperature profile prediction.
- Localized inaccuracy may result when using a 1-D thermal and hydraulic network to apply HTC boundary conditions.

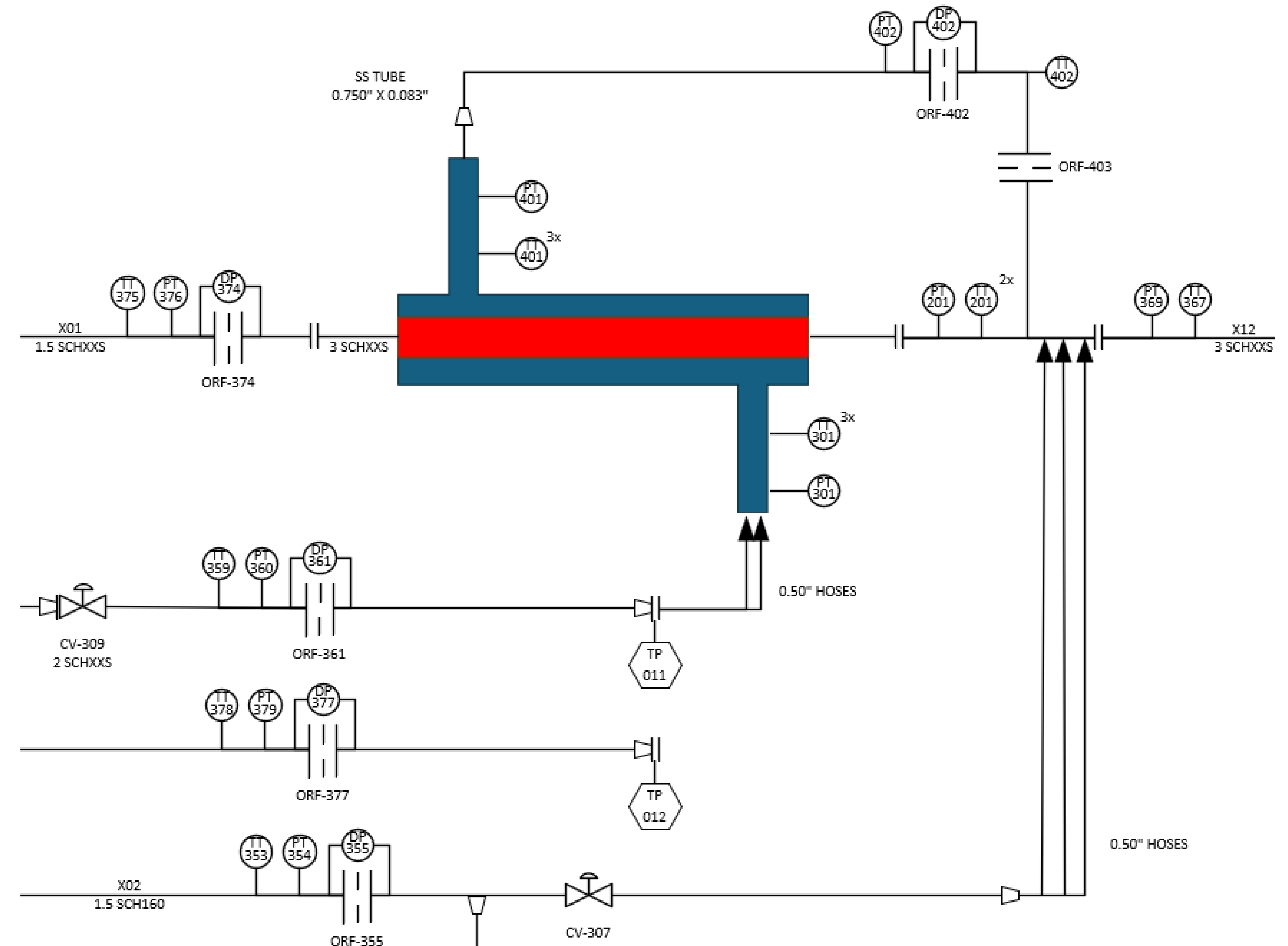
# Test Rationale

- To better enumerate temperature profile uncertainties, testing was completed on a stationary S1B cascade at relevant sCO<sub>2</sub> conditions.
- Uniform crystal temperature sensors (UCTS) were used to measure max temperatures along blade surface for comparison to the same analysis methodology.

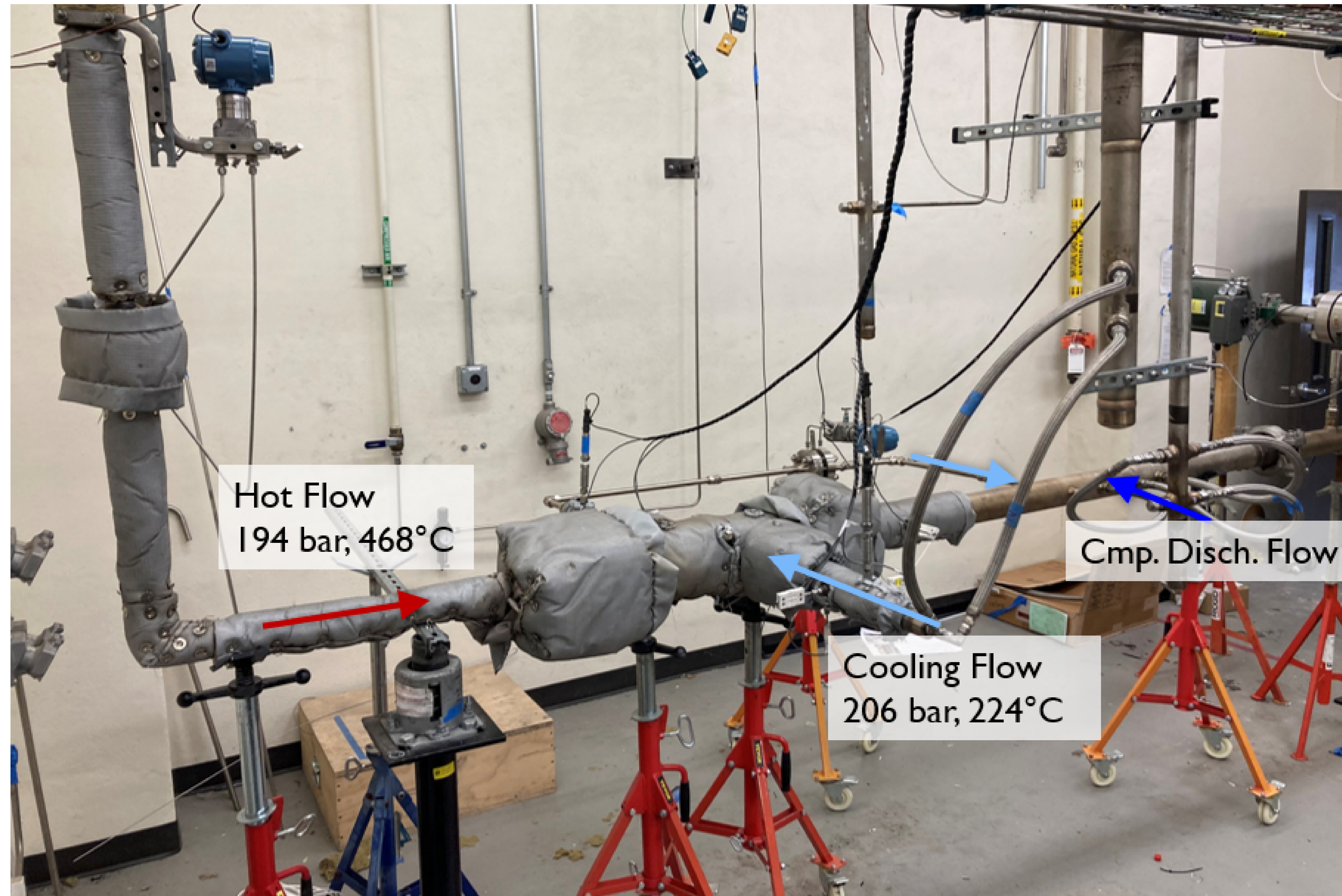
# **SYSTEM DESIGN AND BLADE CASCADE**

# Test Loop Setup

- Testing leverages a 1 MWth scale test loop at SwRI:
  - Primary heater outlet (Hot Flow).
  - Recuperator outlet (Cooling Flow).
  - Compressor discharge (Downstream quench).
- Orifice flow meter attempts measuring differential mass flow to calculate blade cooling flow.
- Restriction orifice generate required pressure differential (15 bar) between blade internal flow and external hot sCO<sub>2</sub> path.

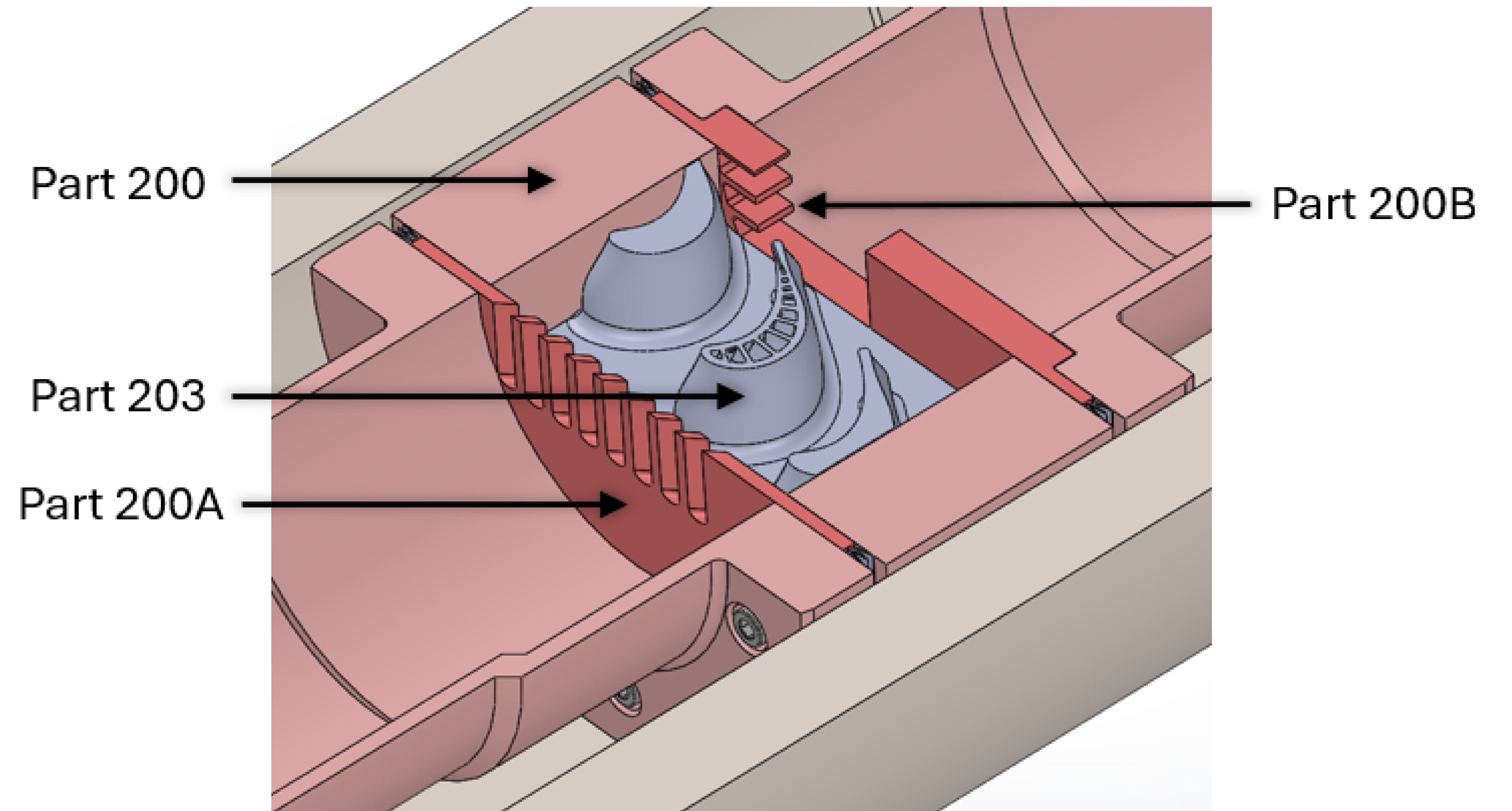


# Test Loop Setup



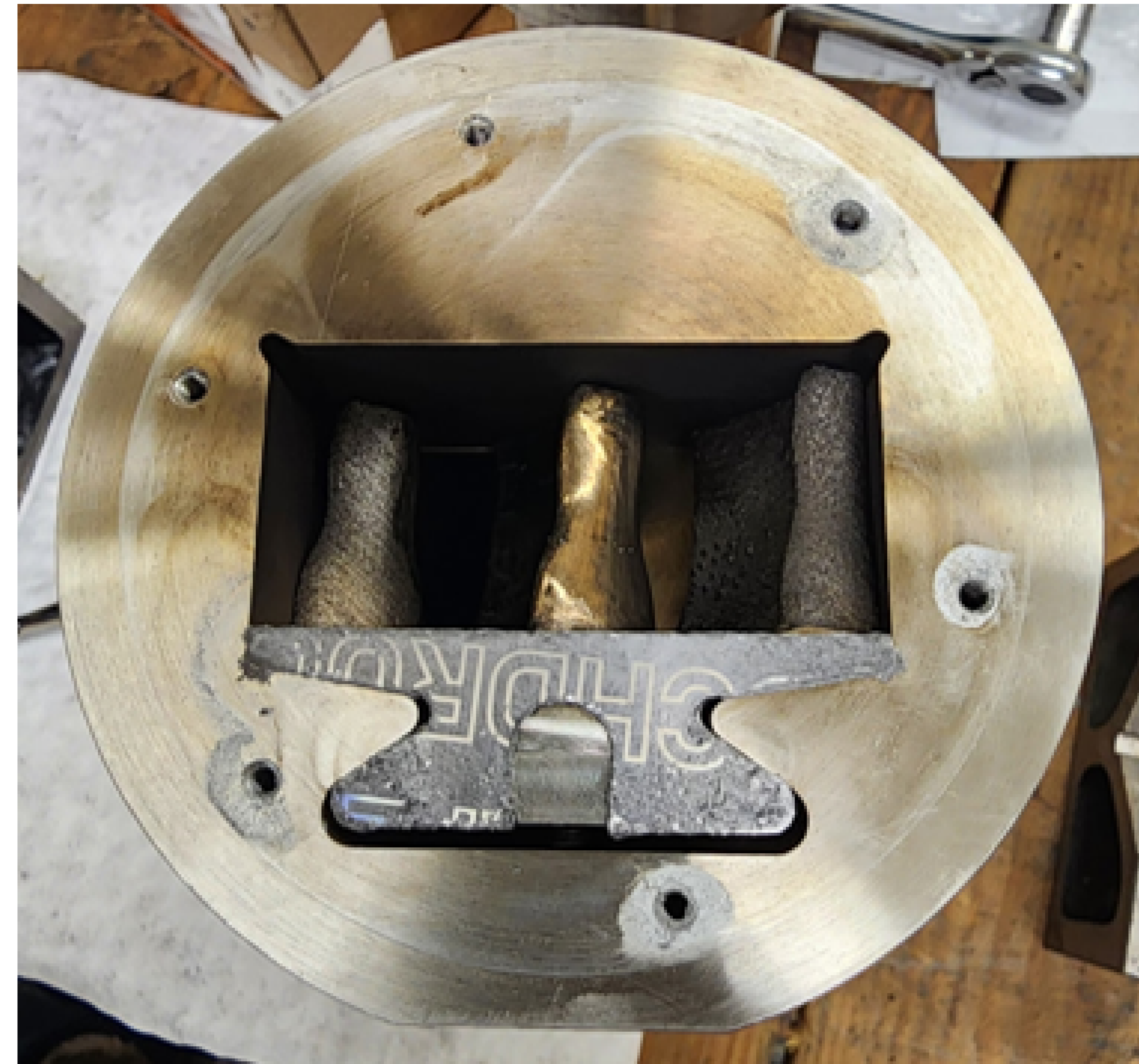
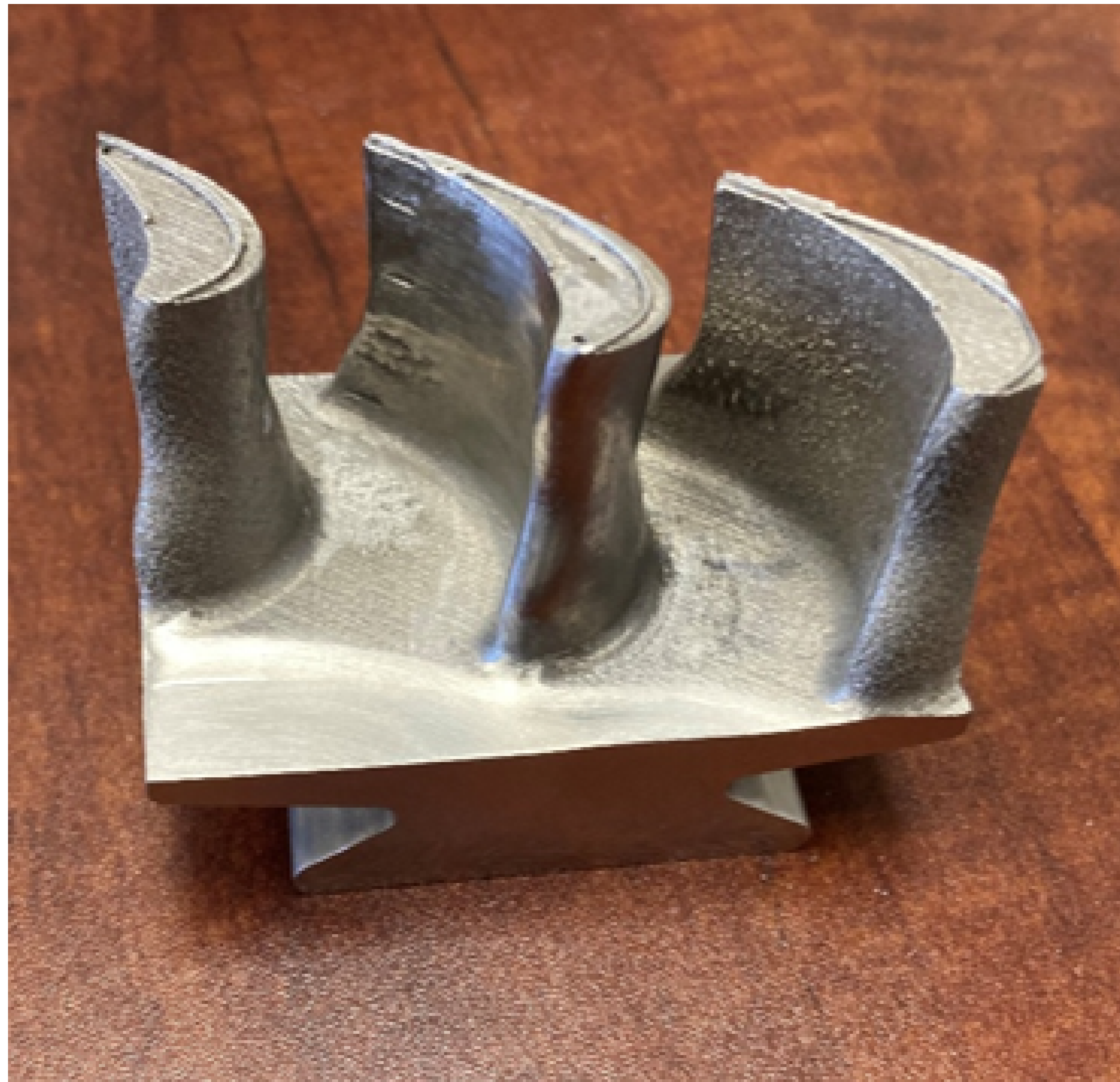
# Blade Cascade Design

- Central blade is an exact replica of the designed S1B with all internal cooling features, neighboring blades provide the relevant flow field.
- The blade cascade was mated to upstream and downstream flow conditioning plates.
  - Upstream plate mimics flow from upstream nozzle.
  - Downstream plate prevents flow separation with swirl brake like features.



Part	Description
203	Blade cascade
200A	Upstream flow conditioning plate
200B	Downstream flow conditioning plate
200	Main insert mating with blade root

# Blade Manufacturing



The blade was additively manufactured using PBF process with Inconel 718 powder. Post-processing steps included heat treatment, grinding external blade surfaces, and EDM of the blade root mating surfaces.

# UCTS Method

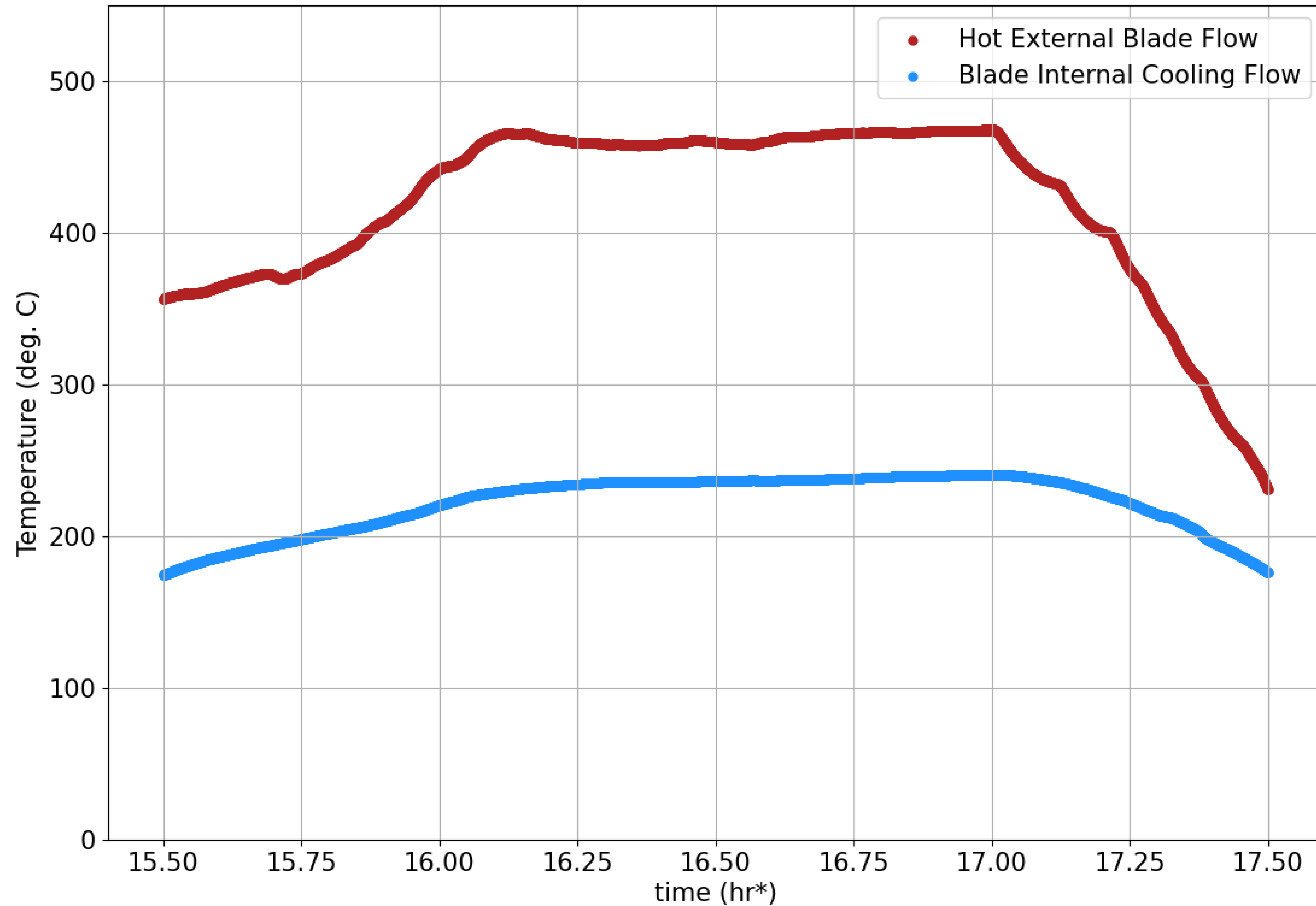
- UCTS were installed by LG-Tech Link Global at 6 locations each on the pressure-surface and suction-surface.
- SiC crystals (0.008 x 0.008 x 0.015 in.) are embedded with an installation process specialized for low wall thickness and harsh turbine environments.
- The SiC are given dislocations, which anneal during testing as a function of the exposure temperature and time duration.
- Post-processing the changes in crystal lattice structure indicated the max temperature seen.

# **TEST OPERATION AND DATA REDUCTION**

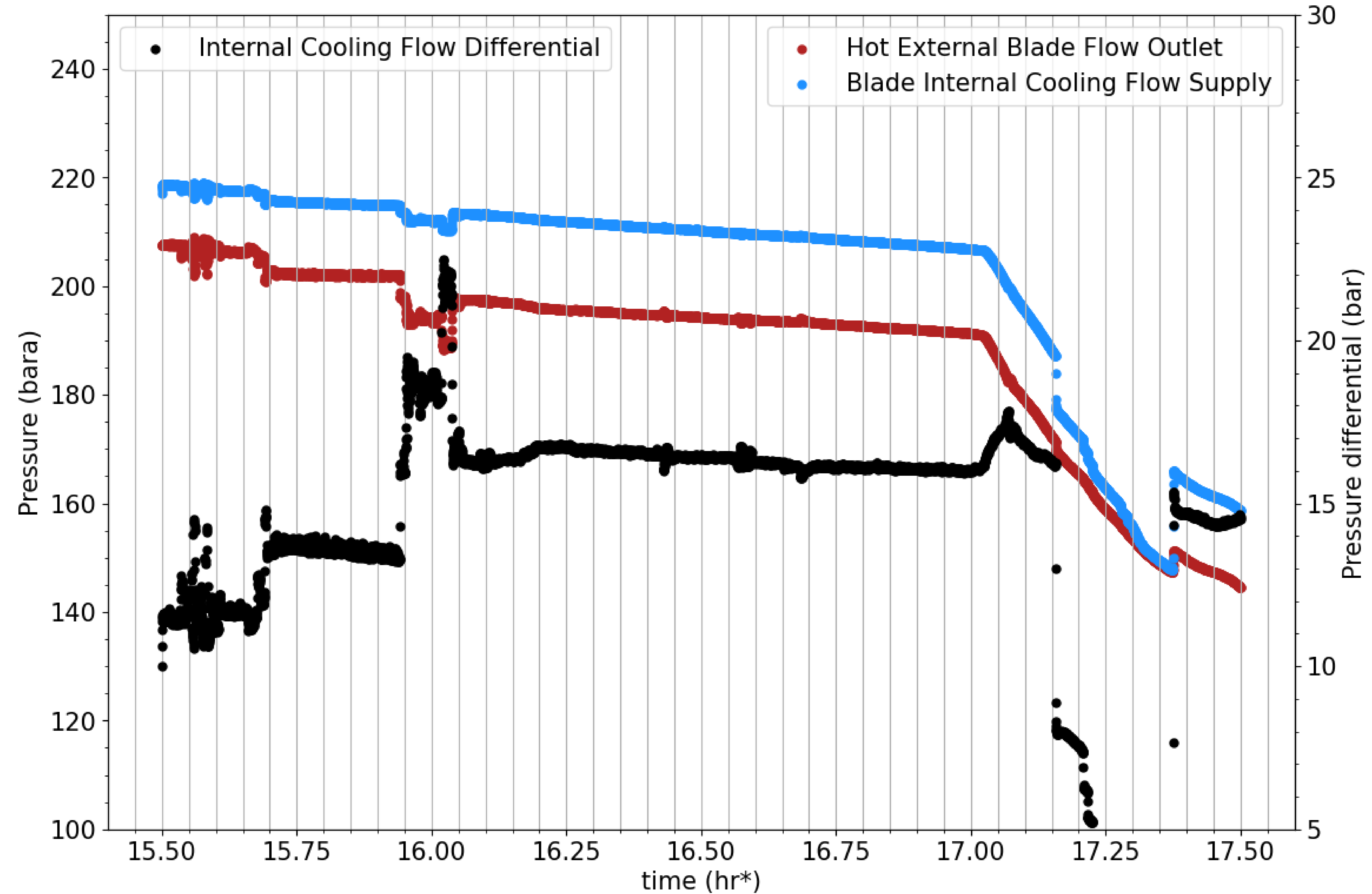
# Test Operation

- **Main objective:** Reach a max blade temperature condition for a stable period of 10 minutes while keeping blade cooling flow rates and external flow conditions nearly constant.
- After initial compressor startup, the primary heater fuel flow was increased to raise the external flowpath temperature.
- Control valves manipulated the respective flow rates of the hot flow and cooling flow.
- The restriction orifice helped stabilize the internal cooling flow rate.

# Results – Temperature Profile



# Results – Pressure Profile

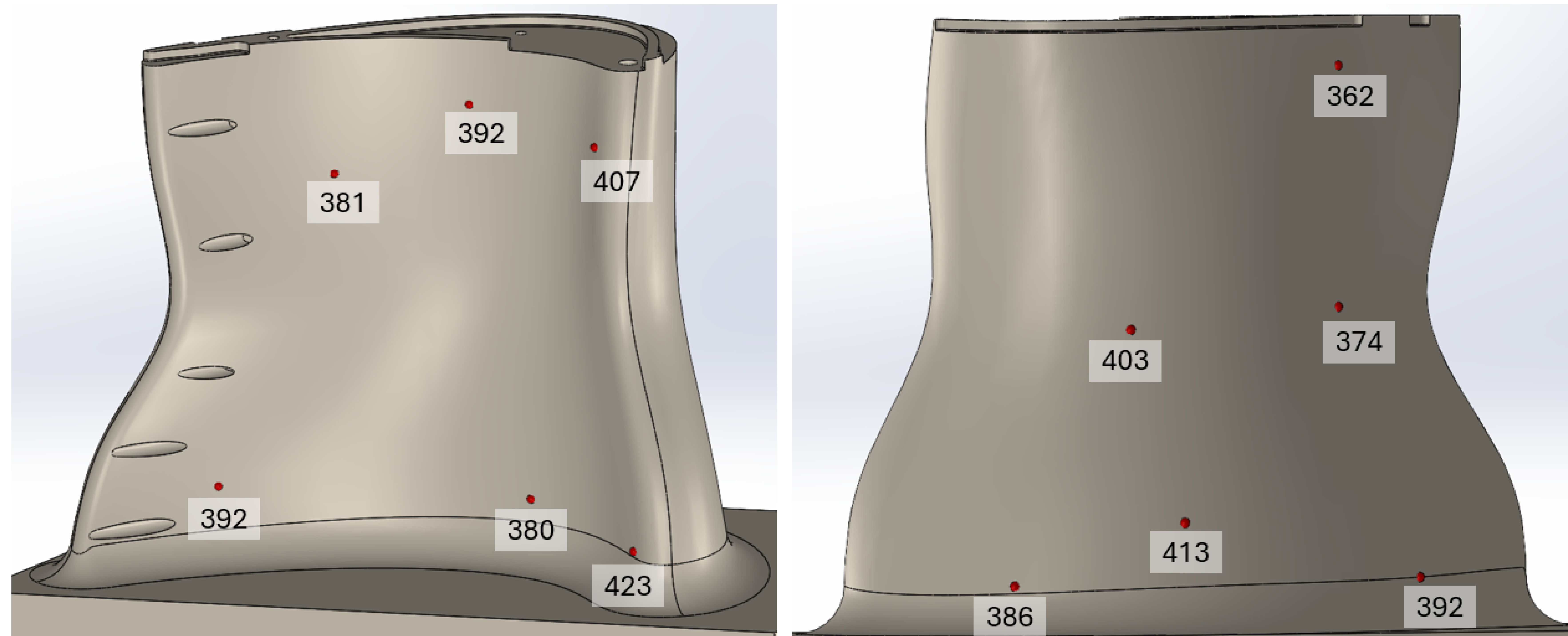


# Flowrate Calculation

Flow Rate	Calculation	Value (kg/s)	Bias Uncertainty
<b>Hot external blade flow</b>	Orifice flow meter (ORF-374)	1.605	±0.8%
<b>Blade internal cooling flow</b>	1-D hydraulic flow network	0.032	±10% (estimated)

- Internal cooling flow is 2% of external hot gas path flow.
- Flow rates through the blade are calculated with the 1-D thermal and hydraulic network. Included:
  - Major and minor pressure losses through the blade passages and pin-fin array.
  - Discharge coefficient ( $C_d = 0.85$ ) for the exit cooling holes based on a velocity head ratio over 100.

# Results – Temp. Profile from UCTS Processing

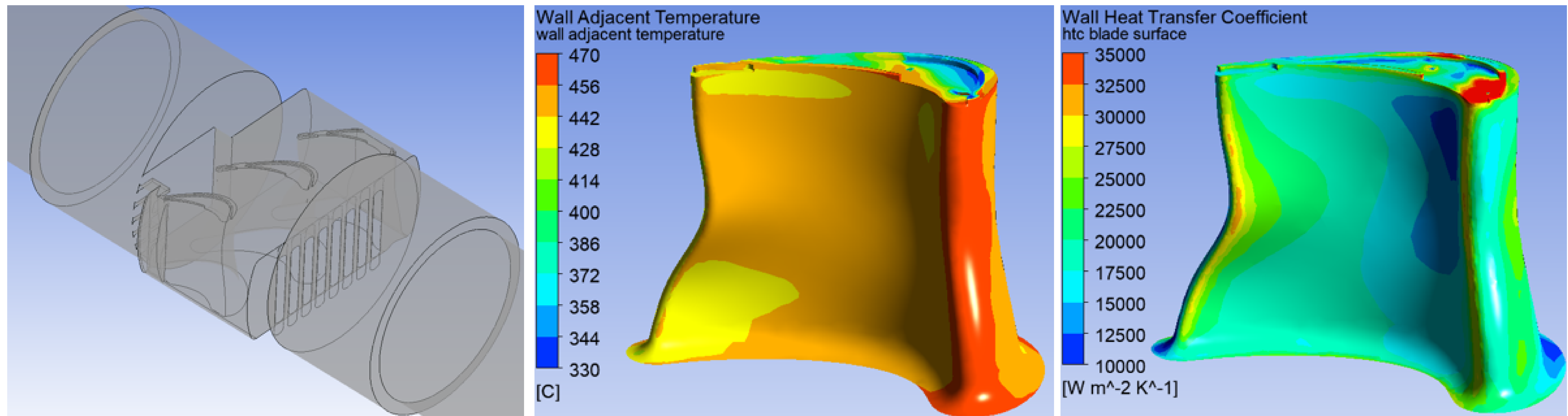


In comparison with the hot external blade flow temperature of  $468^{\circ}\text{C}$ , the cooling flow reduced the metal temperature locally between  $45^{\circ}\text{C}$  and  $106^{\circ}\text{C}$  below the external gas path temperature.

# **ANALYTICAL METHOD**

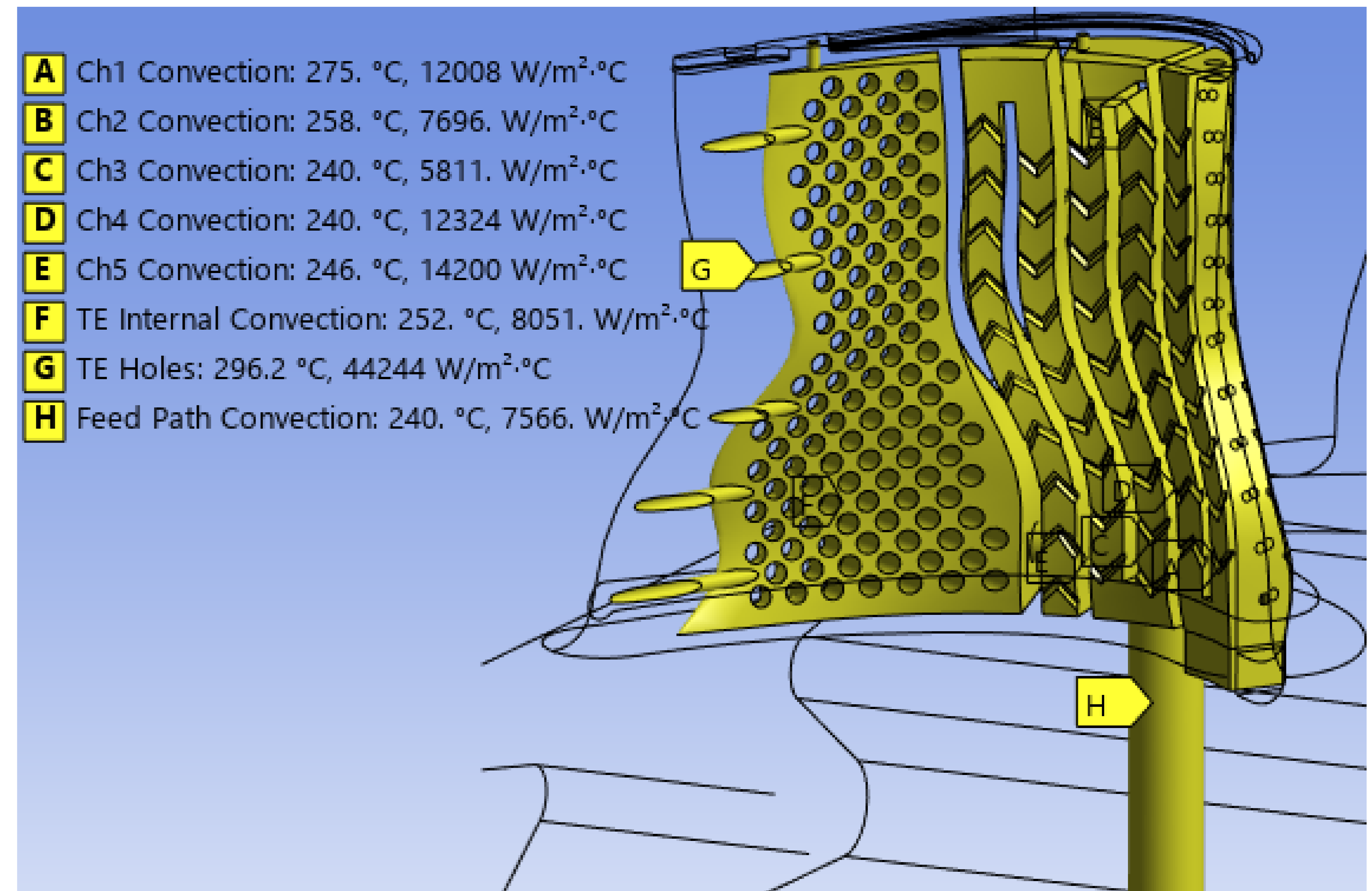
# Analytical Method – External Heat Load

- CFD was used to obtain external blade heat transfer conditions, utilizing ANSYS CFX with a SST turbulence model and CO2 real gas tabulated fluid properties from NIST REFPROP.
- Boundary conditions set according to the measured hot external flow conditions. Point source BC assigned at tip cooling ejection holes to resolve effects on external heat load.
- Blade surface was given a heat transfer coefficient boundary condition of  $6317 \text{ W/m}^2\text{-K}$  and source temperature of  $257^\circ\text{C}$ .

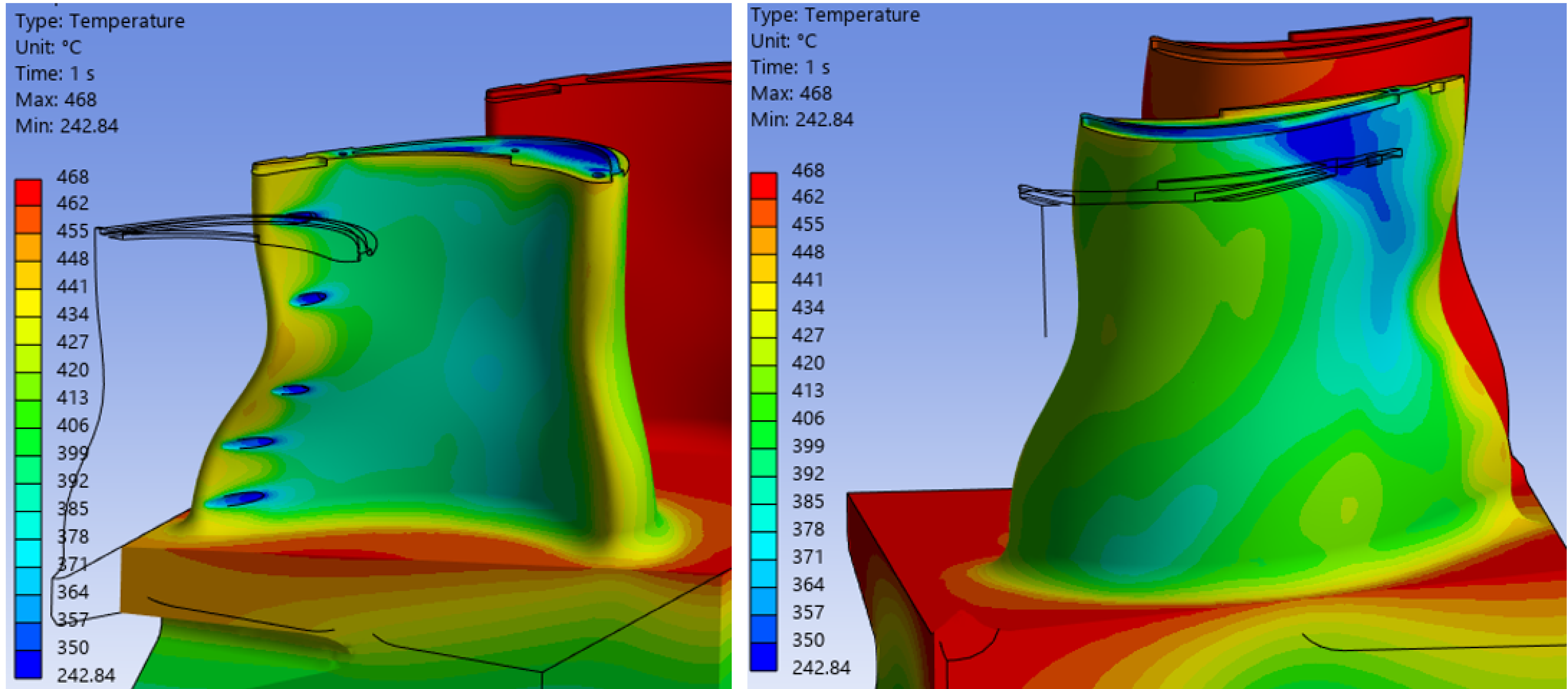


# Analytical Method – Internal Heat Transfer

- 1-D thermal and hydraulic network generates the heat transfer boundary conditions for the ANSYS 3-D thermal model.
- Boundary conditions for the 1-D model include internal cooling feed pressure and temperature, external hot flow downstream static pressure.
- 1-D network calculates HTC's for LE impingement, mid-section ribbed serpentine passages, and TE pin fin array to agree with experimental work.
- Cooling flow predicted through hydraulic and discharge coefficient equations.
- Internal flow temperatures in passages are calculated assuming an average blade surface temperature and a total thermal resistance across the blade walls and internal cooling flow.



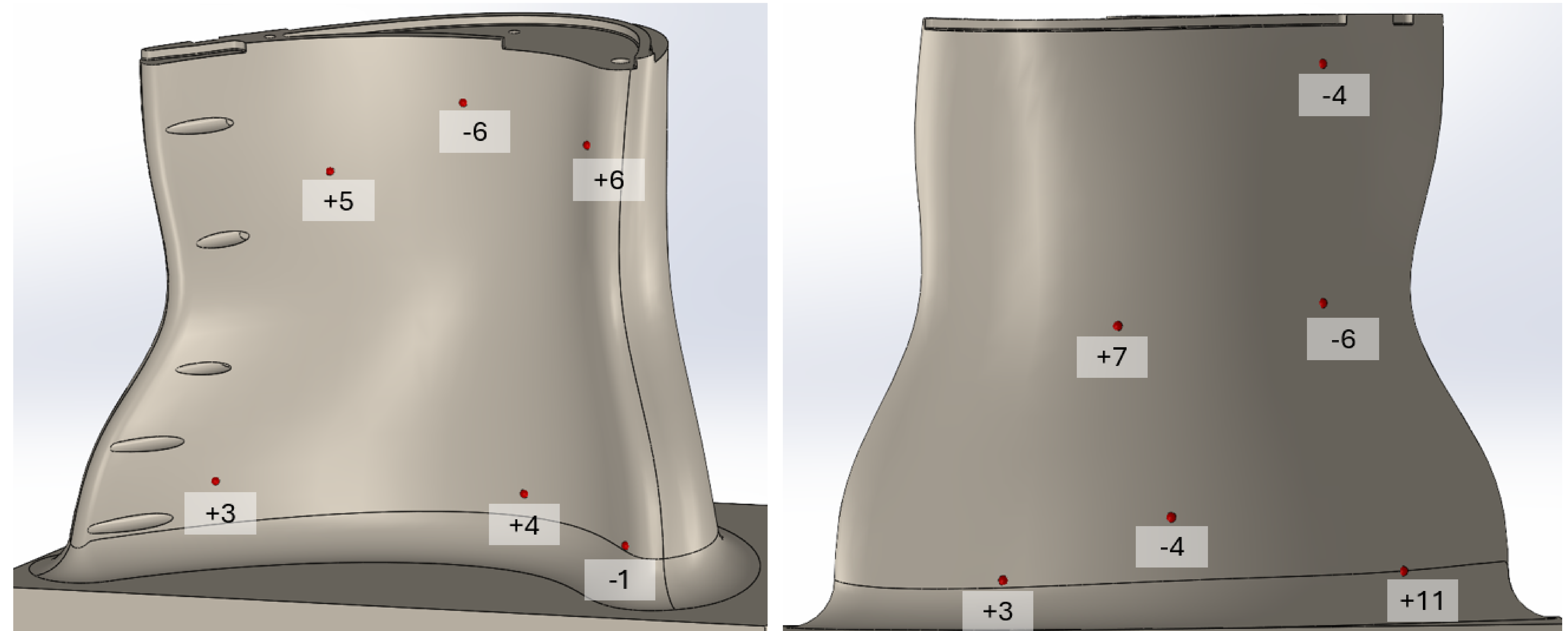
# 3D FE Thermal Results



Employs tabulated thermal conductivity properties for Inconel 718.

# Comparison

- The nodal results with closest proximity to UCTS sensor coordinates are directly compared.
- Average absolute temperature difference is 5.0°C.
- UCTS test values have an expected random error of measurement with standard deviation of  $\pm 3.3^\circ\text{C}$ .



Location	UCTS temp (°C)	Predicted temp (°C)	Difference (°C)
PS1	423	422	-1
PS2	407	413	+6
PS3	381	386	+5
PS4	392	386	-6
PS5	392	395	+3
PS6	380	384	+4

Location	UCTS temp (°C)	Predicted temp (°C)	Difference (°C)
SS1	392	403	+11
SS2	413	409	-4
SS3	386	389	+3
SS4	374	368	-6
SS5	362	358	-4
SS6	403	410	+7

# Conclusions

- With an average absolute deviation of 5.0°C over 12 locations and a maximum of 11°C, the analysis methodology is judged to be of high value for predicting cooling flow requirements and blade life early in a detailed design phase.
- The use of 1-D thermal networks for resolving internal cooling can save considerable time during design iteration when compared to use of 3-D CFD.
- The early stages of the design phase could also leverage empirical correlation based external heat load predictions.
- Future work:
  - Testing rotating internally cooled blades for direct-fired application.
  - UCTS instrumentation for sCO<sub>2</sub> turbine nozzles employing film cooling.

# References

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# QUESTIONS