Supercritical CO_2 Power Cycles Symposium

ECHOGEN power systems

Experimental Demonstration of a Coal Fired Primary Heat Exchanger in a sCO_2-based Power Cycle

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Project Team and Discussion Agenda

Project Team

- Brigham Young University
- Reaction Engineering International
- Riley Power, Inc (Babcock Power)
- Echogen Power Systems
- Linde
- San Rafael Energy Research Center (SRERC)

Agenda

- SRERC Test Facility
- L1500 Furnace
- Furnace Modeling
- Primary Heat Exchanger Design
- Testing Campaigns
- Conclusions
- Acknowledgments


San Rafael Swell
39.01656°N, 110.50780°W

SRERC Test Facility

Facility Research Focus:
- Nuclear Reactor & Fuel Processing
- Power Cycle Technologies
- Solar Thermal Energy Systems
- Manufacturing

Facility Upgrades
- Electrical
- Piping
- Cooling System
- Auxiliary systems
    - CO_2 inventory system
    - Safety system and equipment
- Foundations and Facilities

Fig4: Satellite View of San Rafael Energy Research Center Facility with L1500 Furnace.

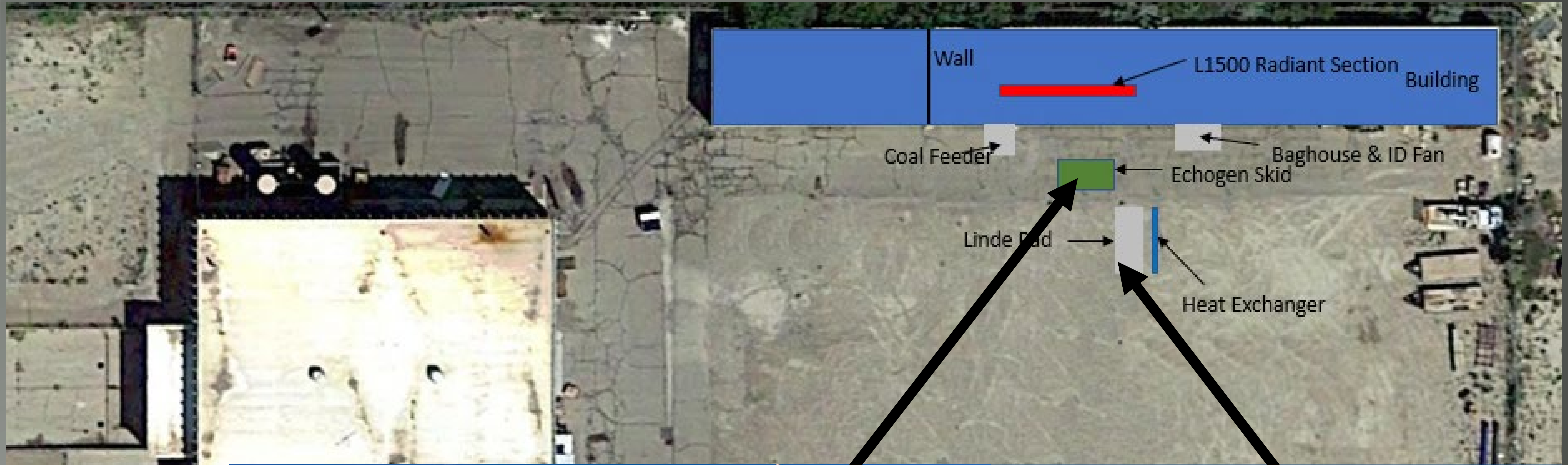


Fig5: Echogen Power Systems Thermal Management System Installed at SRERC.

Fig6: Linde CO_2 Storage Tank Installed at SRERC.

L1500 Furnace

- 1500kW$_{th}$ pilot-scale entrained flow combustor
- 3-zone configuration: radiative, transition and convective sections.
- Refractory lined
- Dual-register, dual-swirl low-NOx burner
- Equipped with primary, inner secondary and outer secondary air injection.

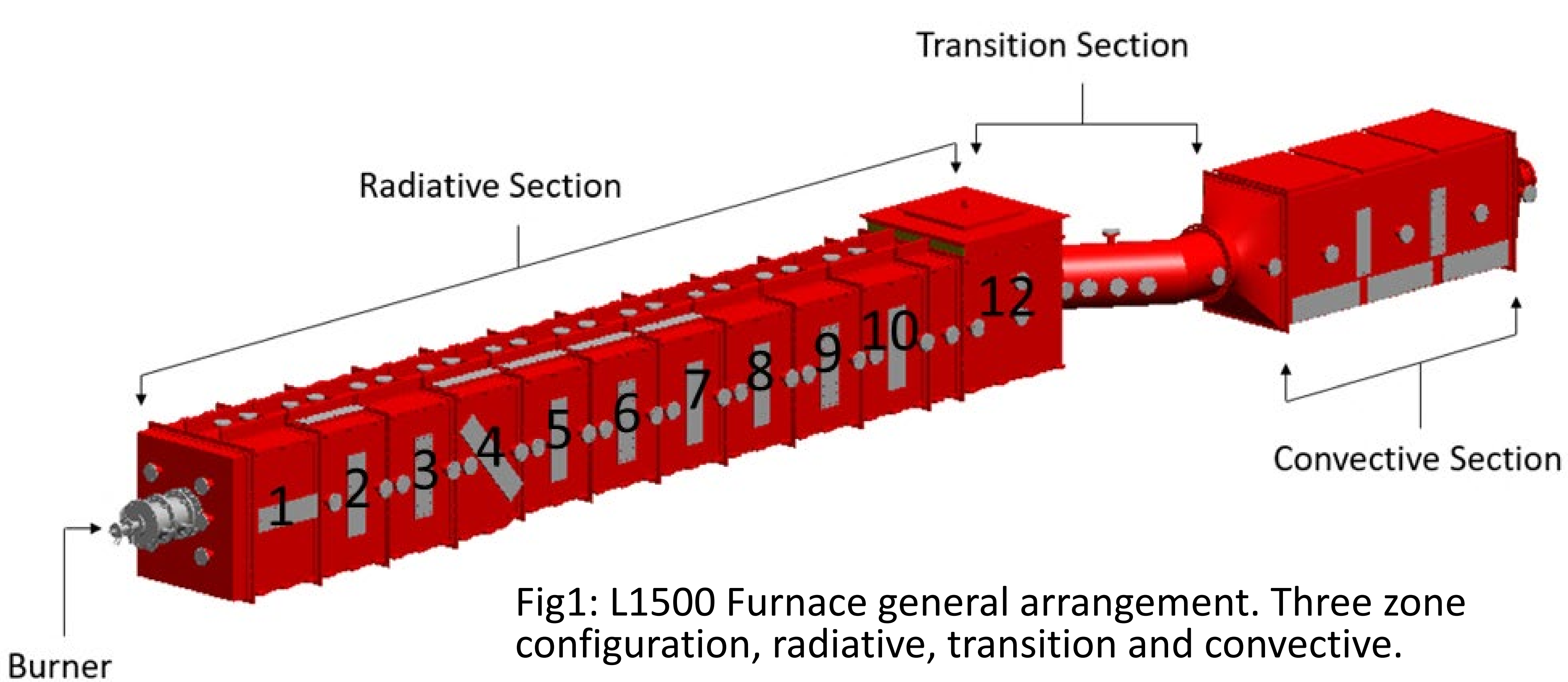


Fig1: L1500 Furnace general arrangement. Three zone configuration, radiative, transition and convective.

Fig2: L1500 Furnace Burner w/Inlet Fuel Manifold

L1500 Furnace Cont.

- Water-cooled, cross-flow heat exchanger in convective section (shown in foreground).
- A baghouse captures particulate entrained in process air.
- Gravimetric feed system with auger screw
- Fuels for this program consist of natural gas and western US bituminous coal.

Fig3: L1500 Furnace. Convective Section (in foreground) with Exhaust Piping and Cooling Manifold.

CFD Modeling

Impact of Firing Rate

- Increasing the firing rate from 0.879MW to 1.76MW (Param2) was effective in enhancing heat transfer.
- A simultaneous increase in excess air played a crucial role in decreasing peak heat flux.

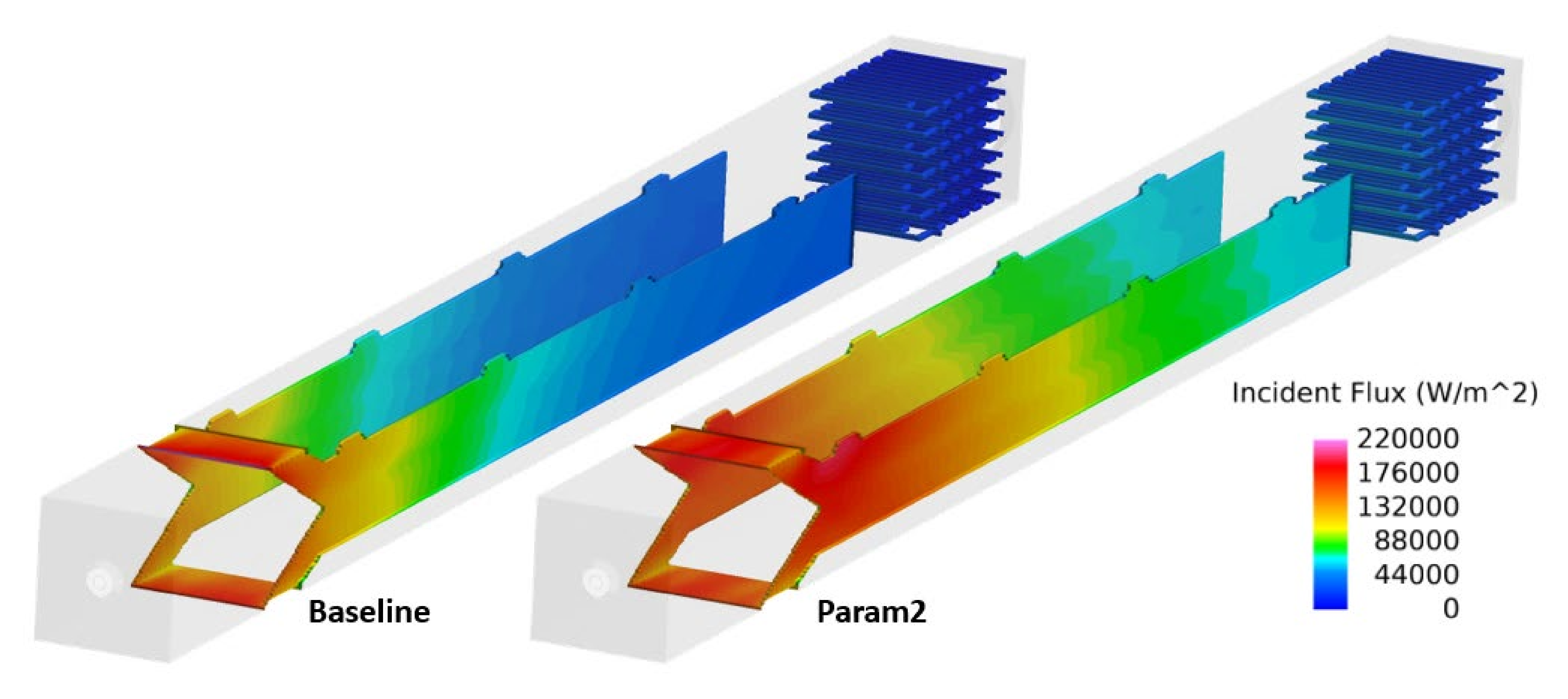


Fig7: CFD Heat Flux Comparison, Baseline and Param2 Cases

	Units	Baseline	Param2
Total PHX Duty	MW	0.632	1.143
Maximum Inc. Heat Flux to PHX	W/m2	218,000	196,000

Table1: CFD Results, Baseline and Param2 Cases

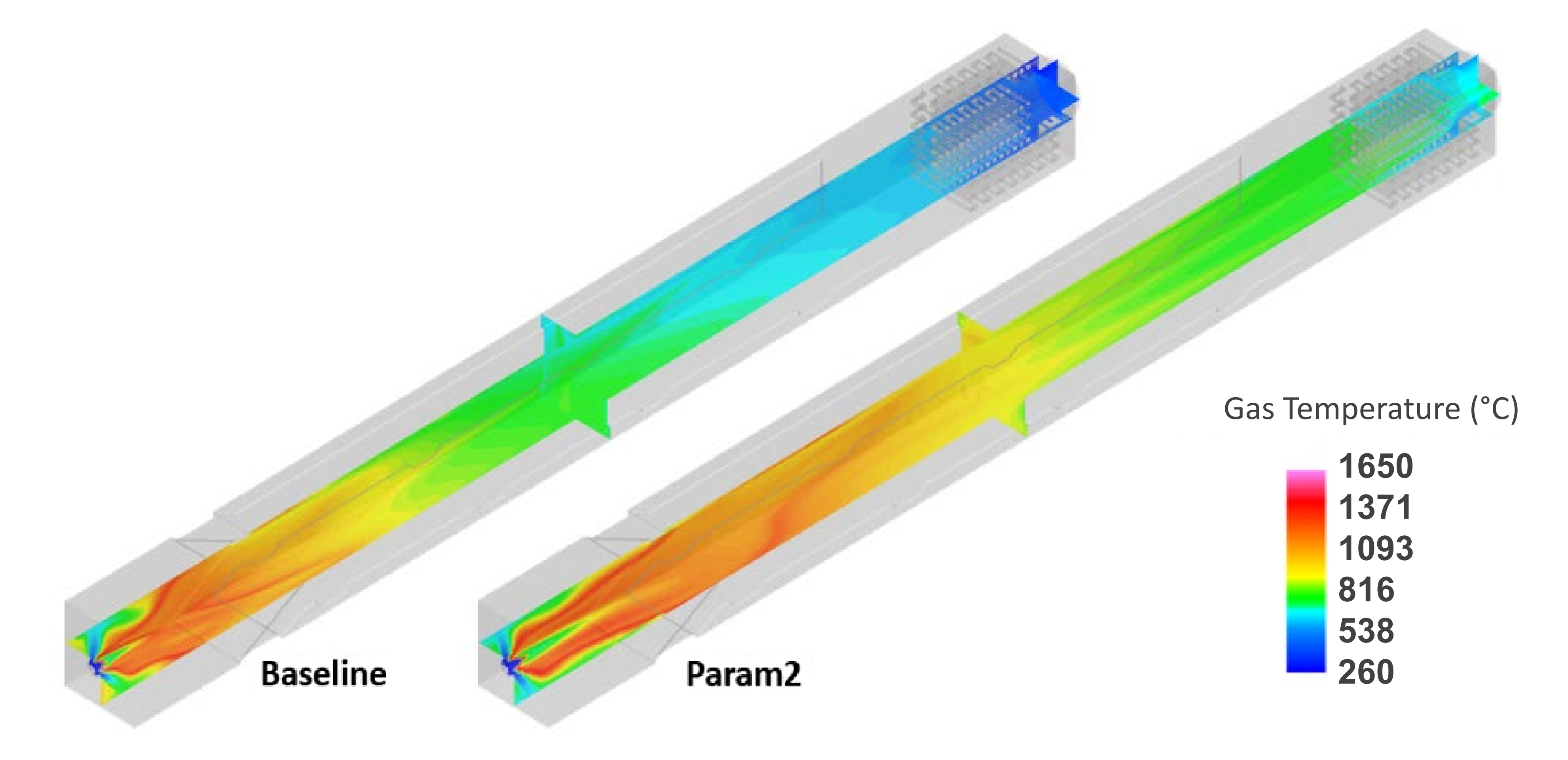


Fig8: CFD Gas Temperature Comparison, Baseline and Param2 Cases

CFD Modeling

Impact of Extended HX Surface

- Extending the heat exchanger by 2ft decreased peak heat fluxes by nearly 6%, as demonstrated in Param6 compared to Param2.
- Param6 was the selected installation option.

	Units	Param2	Param6
Total PHX Duty	MW	1.143	1.135
Maximum Inc. Heat Flux to PHX	W/m2	196,000	185,000

Table2: CFD Results, Param2 and Param6 Cases

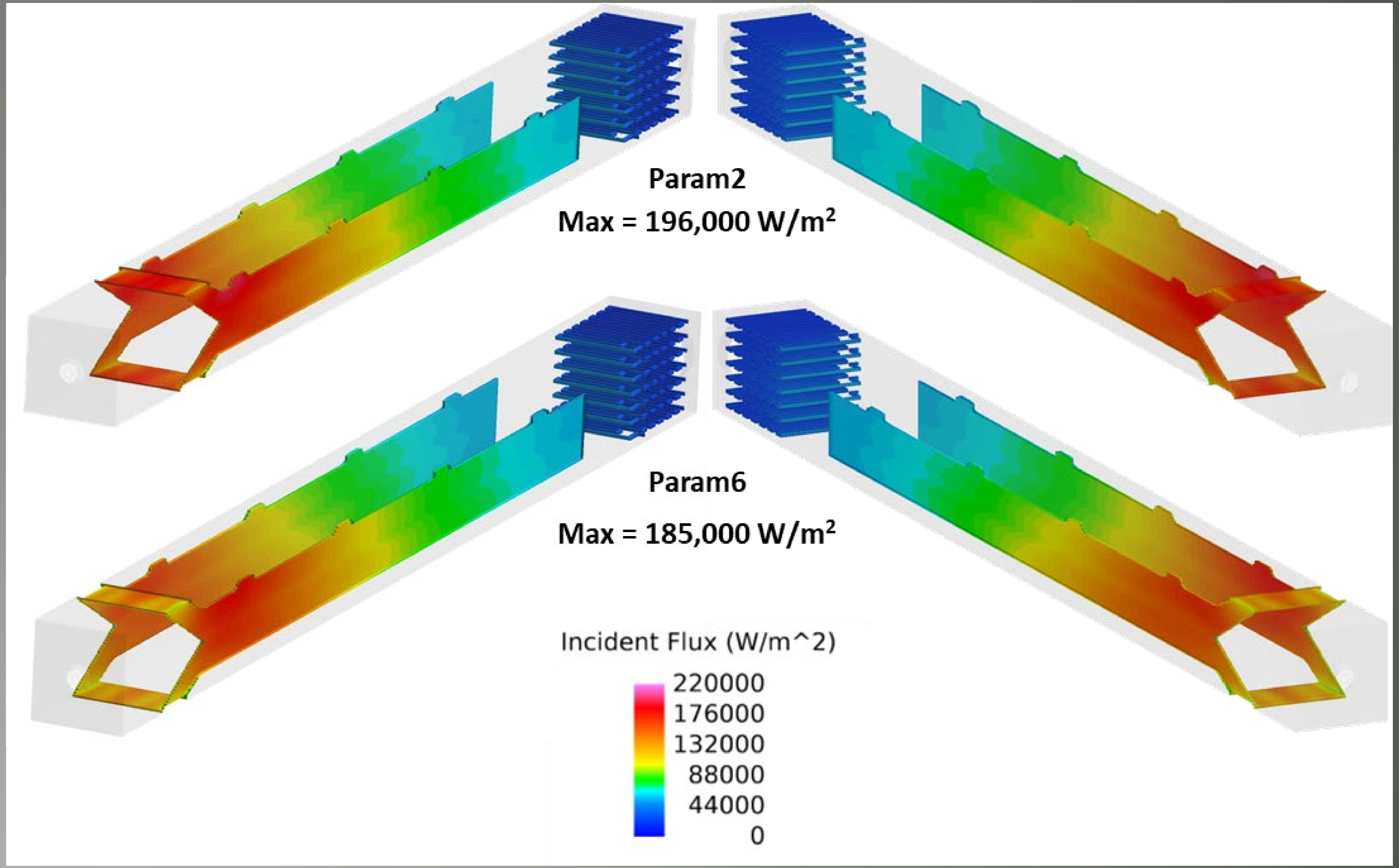


Fig9: CFD Heat Flux Comparison, Param2 and Param6 Cases

CFD Modeling

Impact of Burner Swirl

- Swirl reduction produced a narrower flame sheet near burner
- Higher peak temperatures observed
- Rapid gas mixing yielded substoichiometric combustion and higher fluxes in some cases

Impact of Staging Air

- Staging air elongates the flame, reducing front-end heat flux
- Downstream mixing issues observed producing substoichiometric combustion
- Higher peak temperature
- Increased incident flux

Impact of Bluff Body

- Addition of the bluff body enhanced mixing while extending heat release
- Observed unfavorable peak heat flux due to intensified mixing

CFD Modeling

Impact of Natural Gas Flame

- Running on 100% natural gas
  - Increased heat fluxes at the near-burner end of the radiant section.
  - Produced a substantial increase in peak tube metal temperatures (from 1100°F to 1400°F)
  - Generated a 10% rise in predicted heat transfer to the PHX.

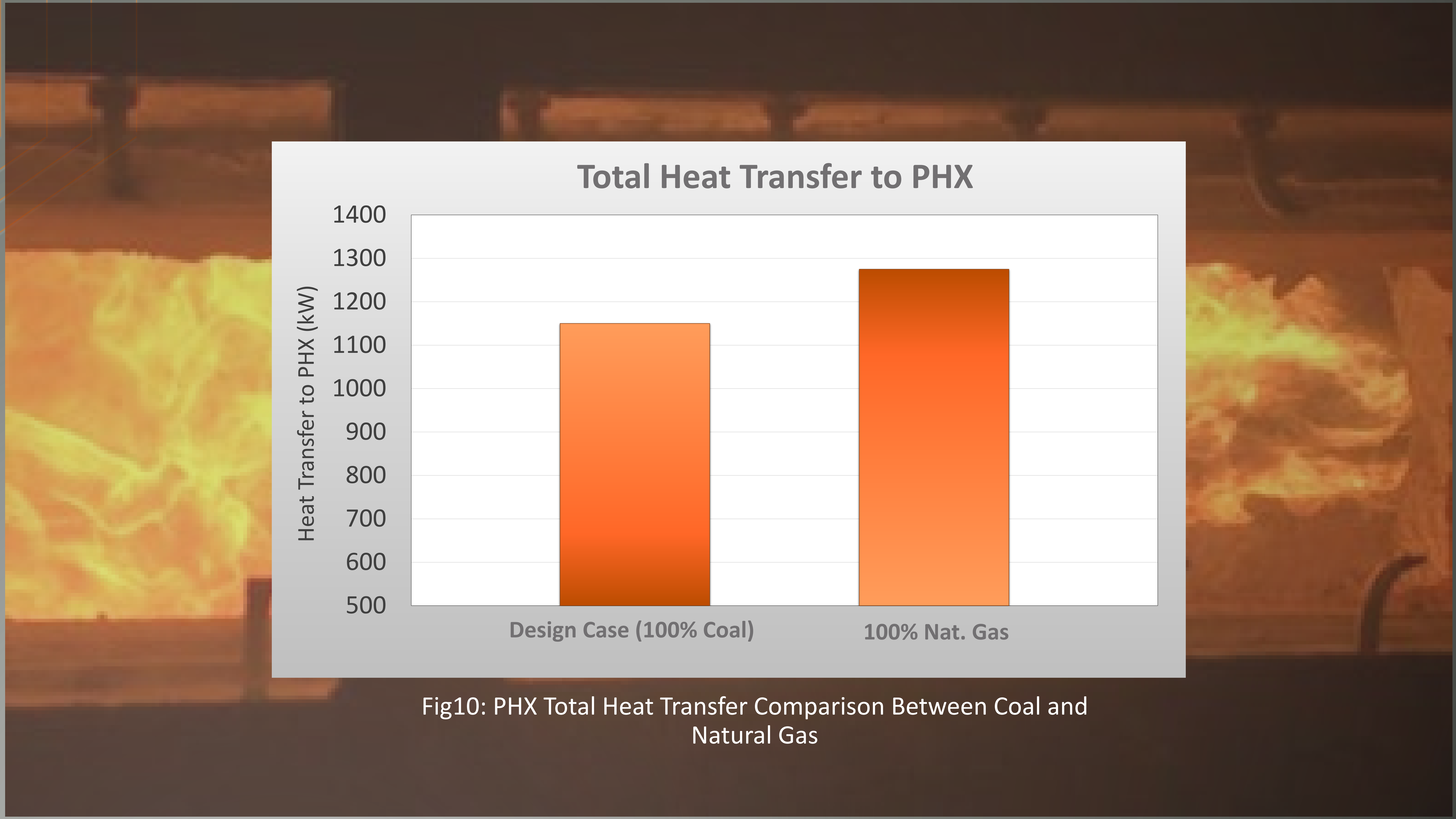


Fig10: PHX Total Heat Transfer Comparison Between Coal and Natural Gas

PHX Design

Design Conditions:

	Units (USC)		Units (SI)	
CO_2 Inlet Temperature	°F	779	°C	415
CO_2 Outlet Temperature	°F	1112	°C	600
CO_2 Flow Rate	lb/hr	43640	kg/s	5.5
CO_2 Operating pressure	PSIA	2955	MPa	20.37
Max Allowable Working Pressure	PSIA	3975	MPa	27.41

- Tangent wall design per ASME Sect.I
- Material selection Super 304H
- Limited surface area due to retrofit application.
- Sensible heat transfer presented design challenges
- Managing heat flux is critical for maintaining PHX integrity.

Fig11: Primary Heat Exchanger (PHX) Installation

PHX Design

- Embedded heat flux sensors aid in verifying thermal modeling
    - 6 Locations
    - Qty: 2, Near-wall
    - Qty: 2, Mid-wall
- Flow balancing valves are used to manage flow distribution and maintain desire flux levels.
- Skin thermocouples monitor tube metal temperatures.

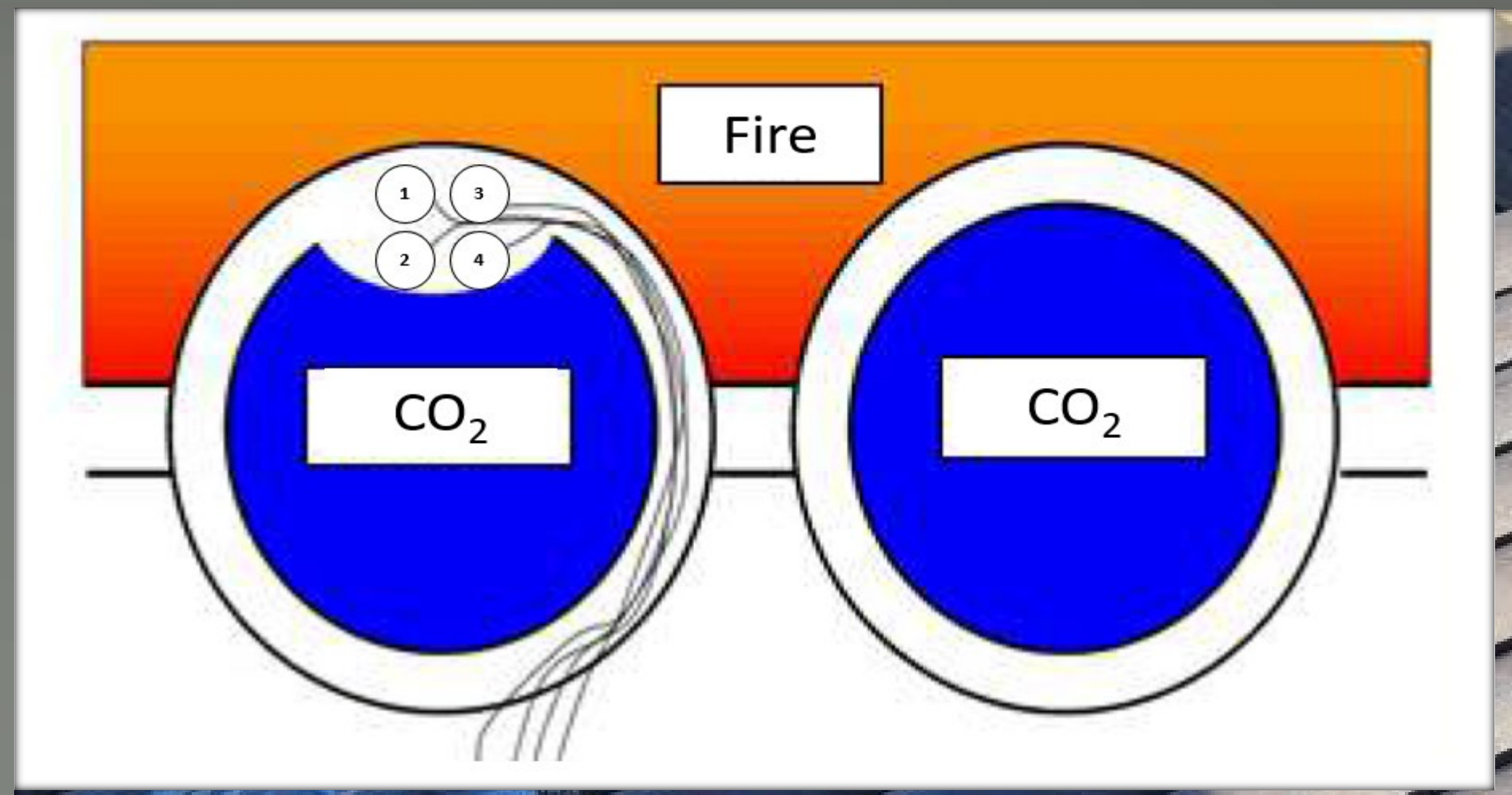


Fig12: (Right) Heat Flux Sensor General Arrangement

Fig13: Heat Flux Sensors Installed on PHX Piping.

Fig14: (Right) Flow Balancing Valve Installation with Outlet Header.

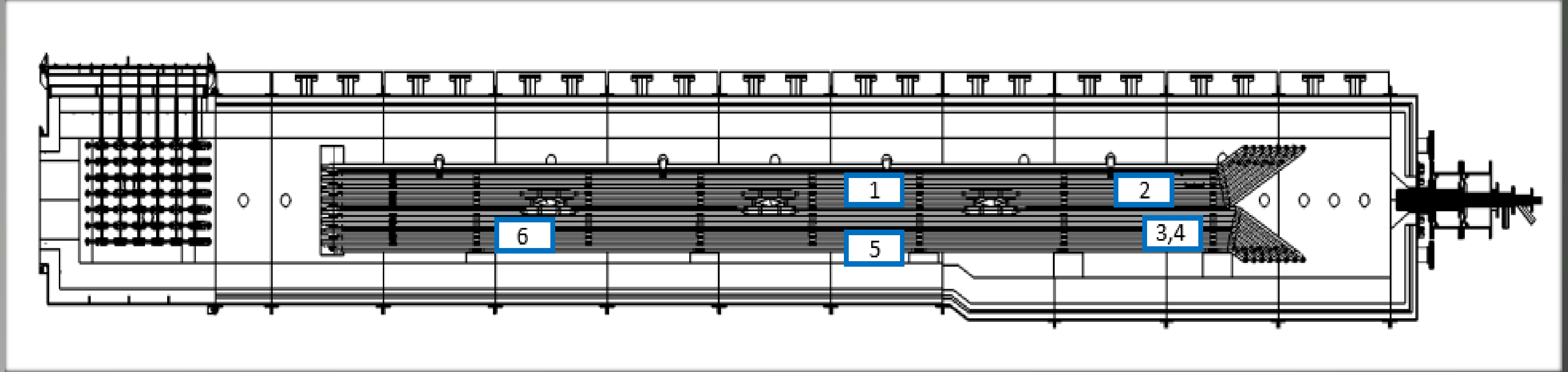


Fig15: L1500 Furnace Elevation with Heat Flux Locations.

PHX Design

- Heat transfer model aligns well with test data for the radiant module but significantly differs in the convective section due to observed fouling.
- Thermal resistance assumptions impacted sCO_2 exit temperature predictions.
- PHX efficiency = 60-65% (meets predictions).
- Peak heat input of 1.63MW from fuel.
- Adjusting sCO_2 flow rate demonstrated the capability to achieve full design conditions.

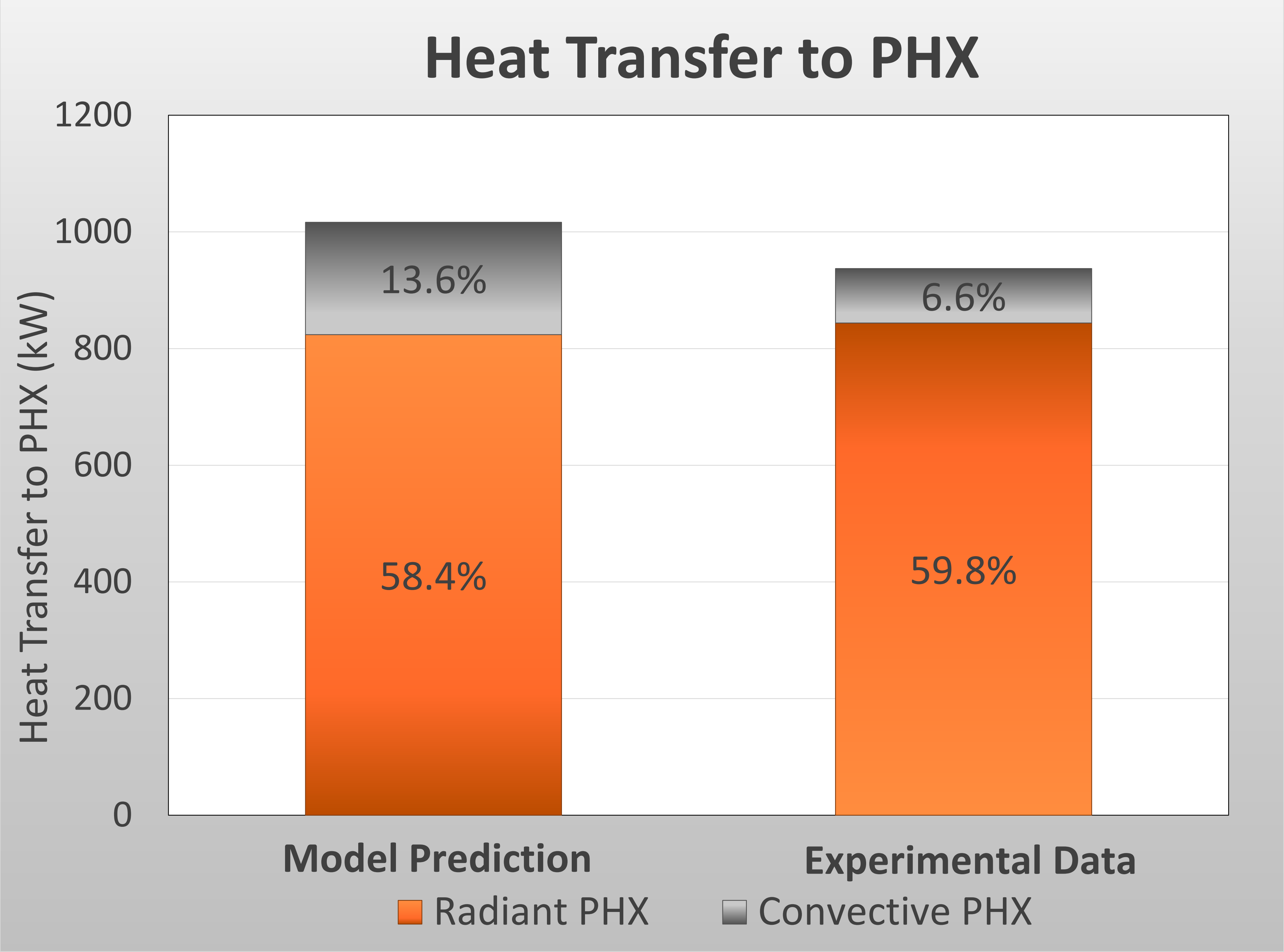


Fig18: Comparison of Heat Transfer to PHX for Coal vs Natural Gas at 1.76MW Firing Rate

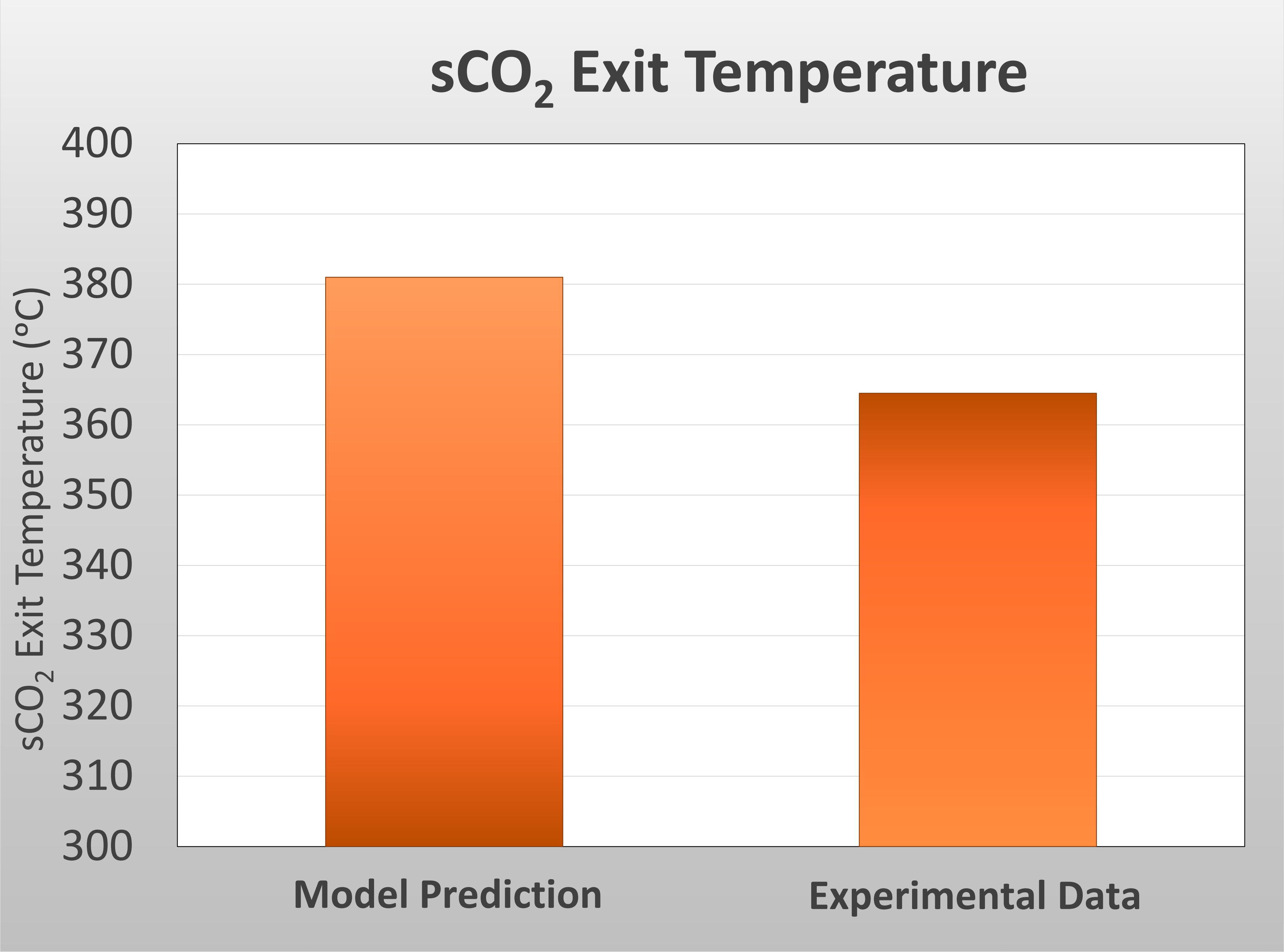
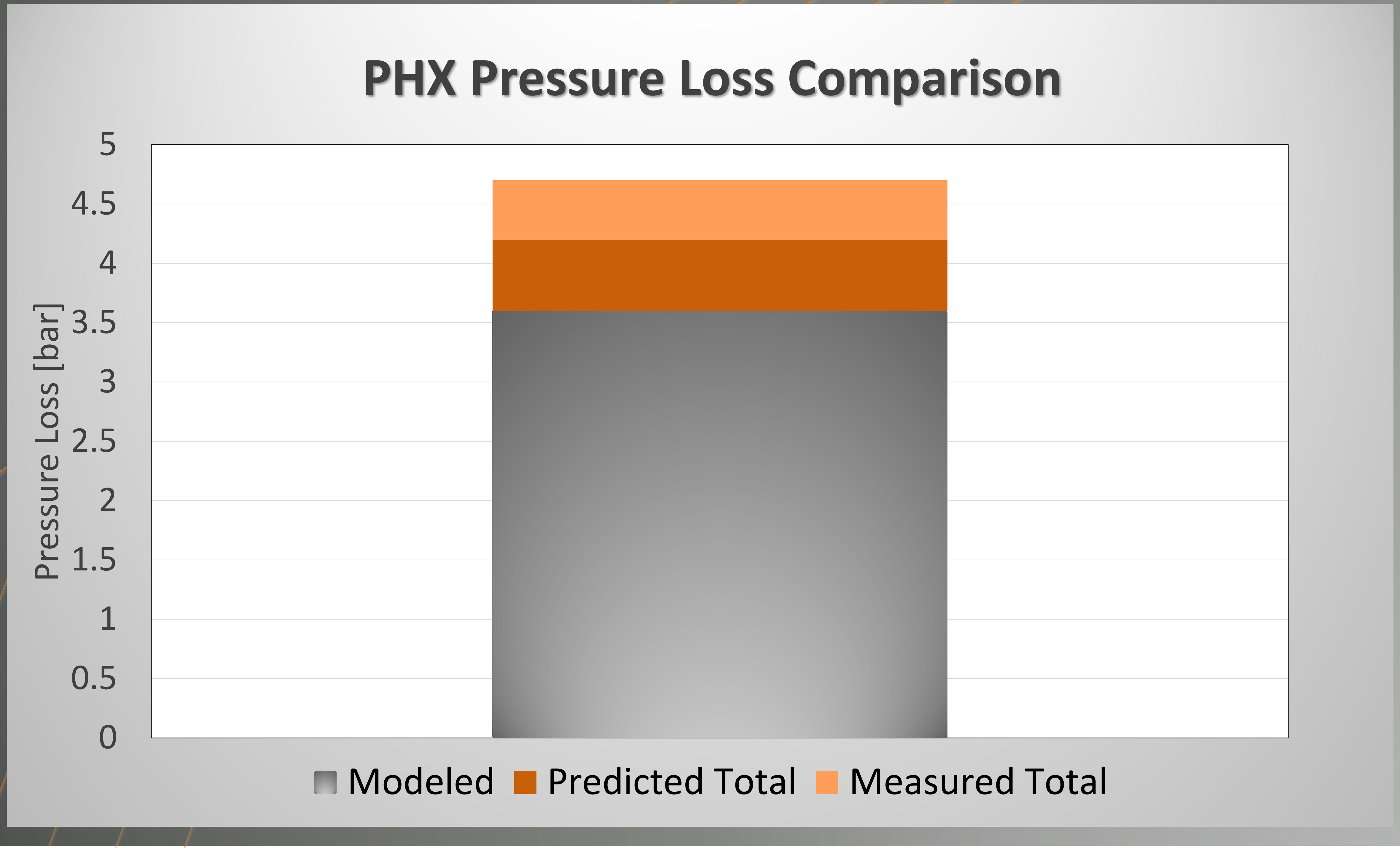


Fig19: Test Data Comparison of sCO_2 Exit Temperature Showing Impacts of Reduced Overall Heat Transfer to PHX

PHX Design

- Measured total PHX pressure drop:
  - dP = 4.7bar (68psi)
- Model predicted total PHX pressure drop:
  - dP = 3.6bar (52psi)
- Incorporating valve and piping losses yields a total pressure drop, dP = 4.2bar (61psi, 89%)



- Temperature distribution in the radiant panels aligned well with predictions.

Sensor Position	CO_2 Temps at Convective Outlet °C	CO_2 Temps at Radiant Outlet (unbalanced) °C	CO_2 Temps at Radiant Outlet (adjusted) °C
1	371	552	563
2	370	544	556
3	366	553	565
4	368	547	556
5	367	557	567
6	364	550	555
7	354	551	564
8		556	554
9		61*	59 *
10		548	555
11		554	561
12		560	567
13		562	584
14		583	564
15		563	583
16		590	583

Table3: PHX Tube Temperature Distribution Comparison Between Unbalanced and Adjusted Flow Balancing Valves

Testing

Campaign 1 Achievements

- 1.6MW max heat input to PHX.
- 70hrs continuous operation.
- Heat-soaked start-up operation.

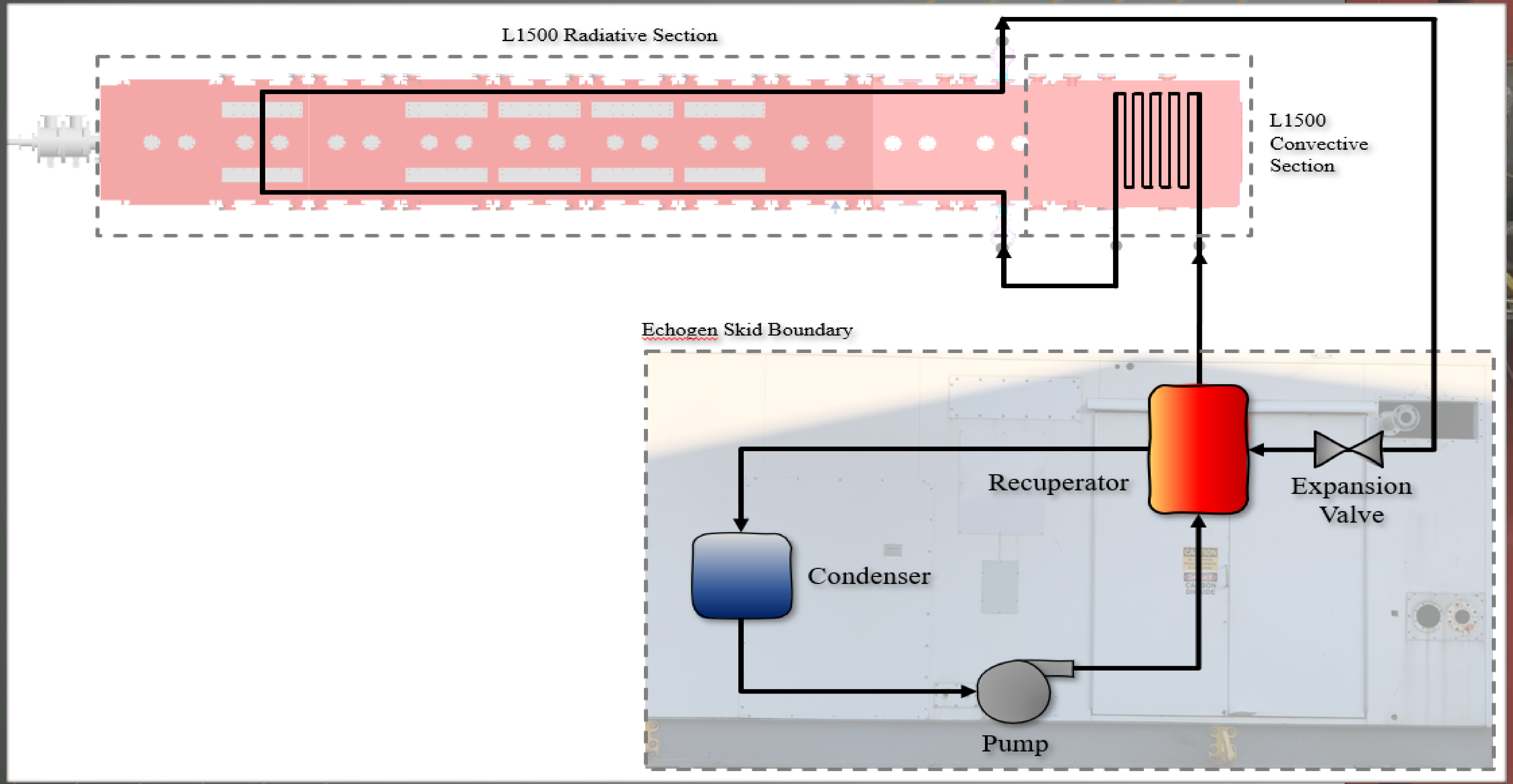


Fig20: Process Flow Diagram for sCO_2 Cycle

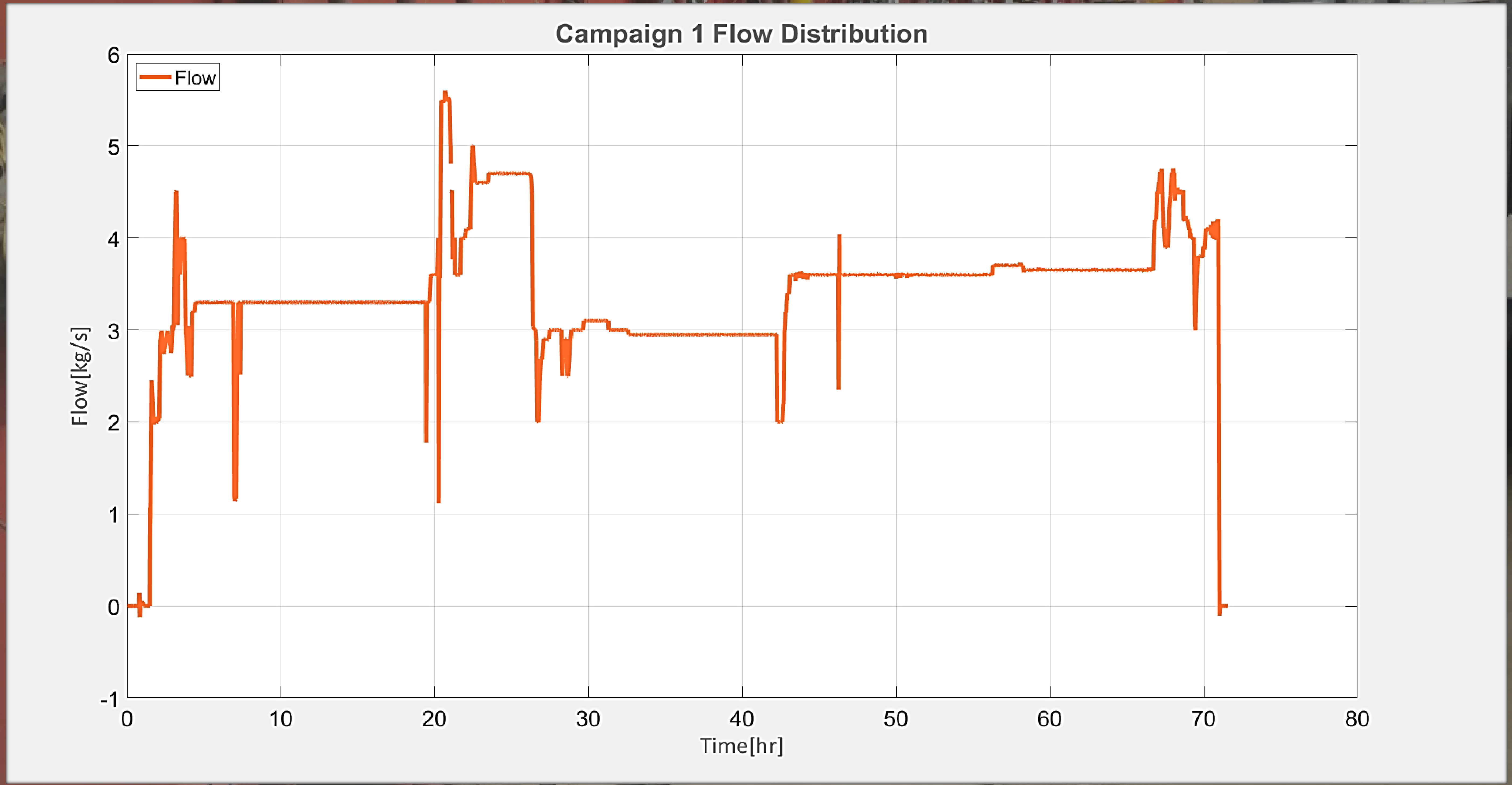


Fig21: Flow Distribution During Campaign 1 Endurance Testing

Testing

Campaign 2 Achievements

- Additional +70Hrs continuous operation.
- Avg. 1MW of heat input to PHX.

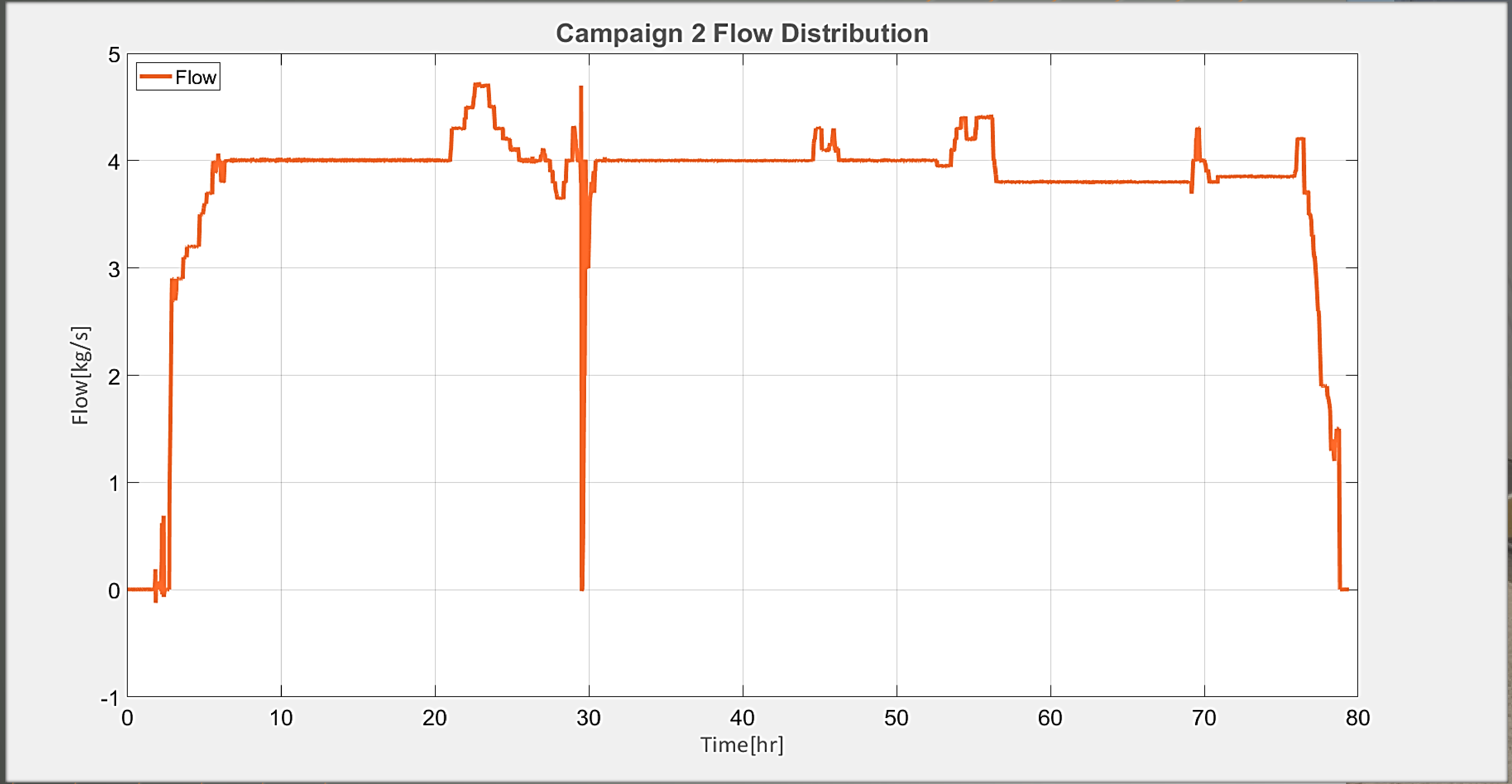


Fig22: Flow Distribution During Campaign 2 Endurance Testing

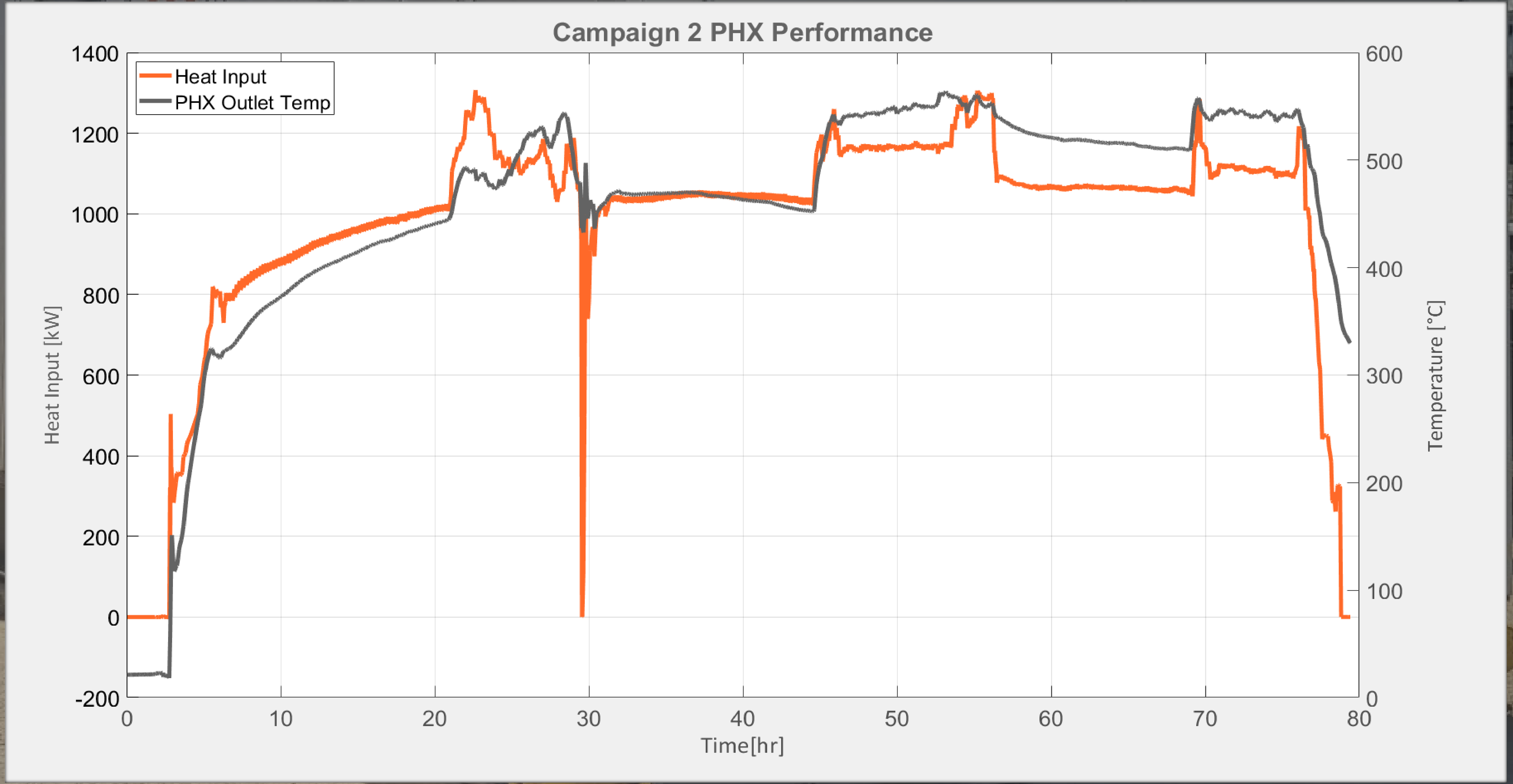


Fig23: PHX Performance During Campaign 2 Endurance Testing

Conclusions

- Increased heat rate of 1.76MW.
- Peak heat flux maintained below 175,000 W/m2.
- Near-burner crossmember arrangement reduces peak heat flux.
- Increased excess air mitigates adiabatic flame temperature.
- Measured data aligns well with model predictions.
- Pressure losses aligned with predictions, and flow distribution improved by adjusting balancing valves.
- Flux sensor readings require further review for accuracy.
- Ongoing testing goals:
    - Obtain full design conditions.
    - Investigate material integrity to reduce risks associated with design and manufacturing.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Acknowledgments

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Brett Bowan: Investigation, Writing.

Timothy Held: Conceptualization, Funding acquisition, Project administration **Andrew Fry:** Conceptualization, Resources, Supervision, Funding acquisition, Investigation.

Brian Schooff: Investigation, Formal analysis, Writing - Review & Editing. **Rajarshi Roy**: Investigation, Formal analysis, Writing - Review & Editing. **Michael D. Johnson:** Methodology, Formal analysis, Investigation, Writing. **Andrew P. Chiodo:** Investigation, Software, Validation, Formal analysis, Writing – Review & Editing, Visualization