Cummins Reversible-Solid Oxide Fuel Cell System Development

Project ID: FE0031971

Lars Henrichsen

April 18, 2023

R-SOFC Project Objectives

Small-Scale Solid Oxide Fuel Cell Systems and Hybrid Electrolyzer Technology Development

Overview

1. 2 year Project ($2M)
2. Component Development to enable $2/kg-H2 by reducing capital cost by 30%
   1. Cell/Stack
   2. Steam Ejector Fuel Loop
3. Project
   1. System Modeling
   2. CFD/Performance Simulation
   3. Experimental (Steam Ejector)
4. Deliverables

   Phase 1
   1. New Cell Design
   2. Steam Ejector Design/Test

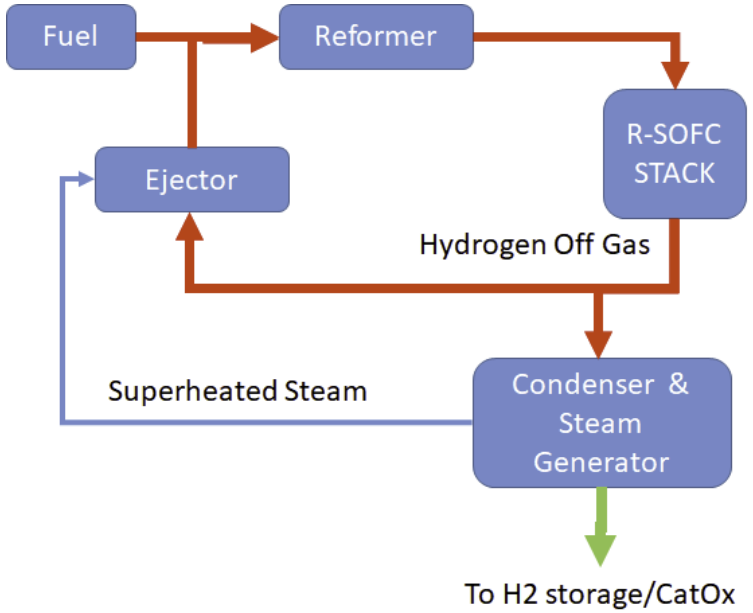
   Phase 2
   1. Prototype Cell Substrate
   2. Steam Ejector Demo. in hot fuel loop experiment

1. NextGen Cell & Stack Design

Produce a metal substrate with higher performance and lower cost

2. Steam Ejector Concept Design

Demonstrate a steam ejector in a simulated hot fuel loop



Budget and Milestones

Complete

In Progress

Timeline and Budget

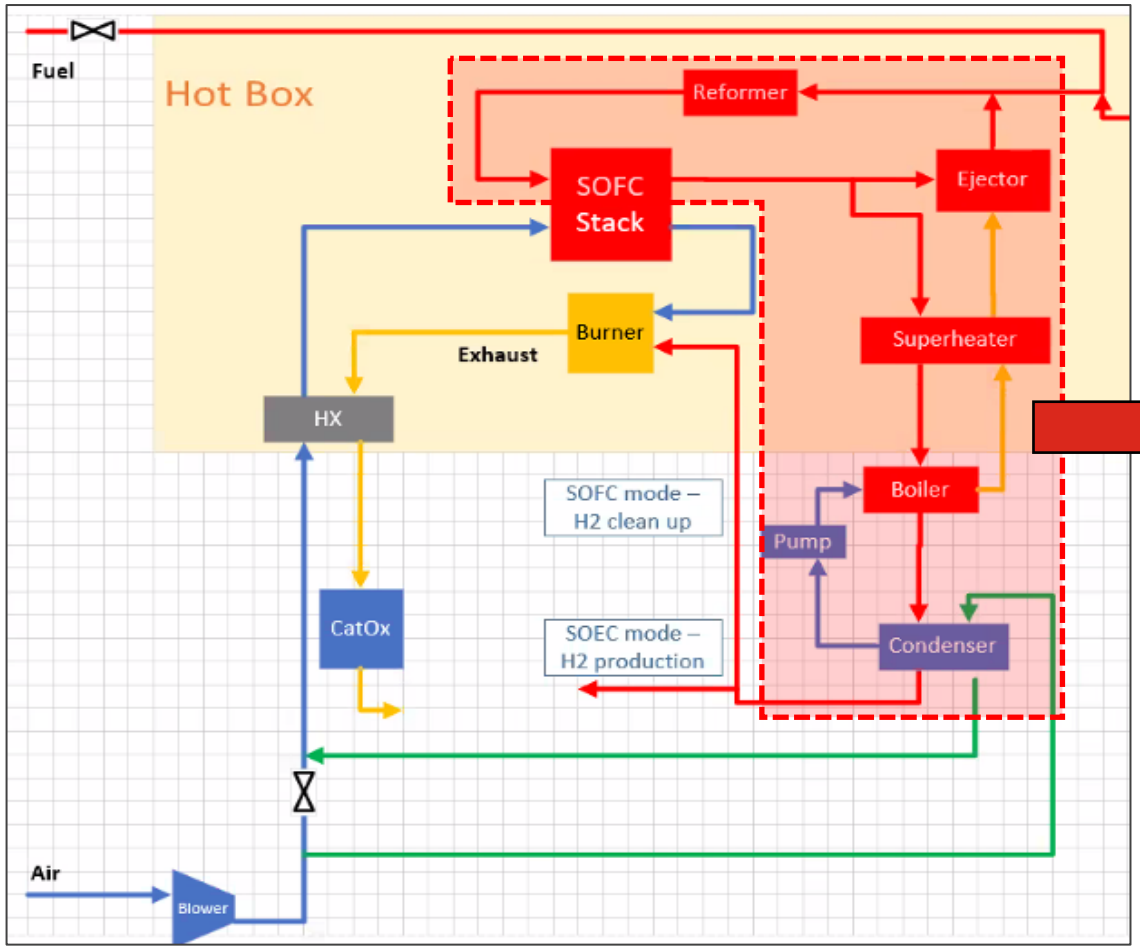
- Project Start Date: January 1, 2021
- Project Duration: 24 months
- Total Project Budget: $2,501,031
  - Total DOE Share: $2,000,825
  - Total Cost Share: $500,206
  - Total DOE Funds Spent*: $1,817,034
  - Total Cost Share Funds Spent*: $458,320

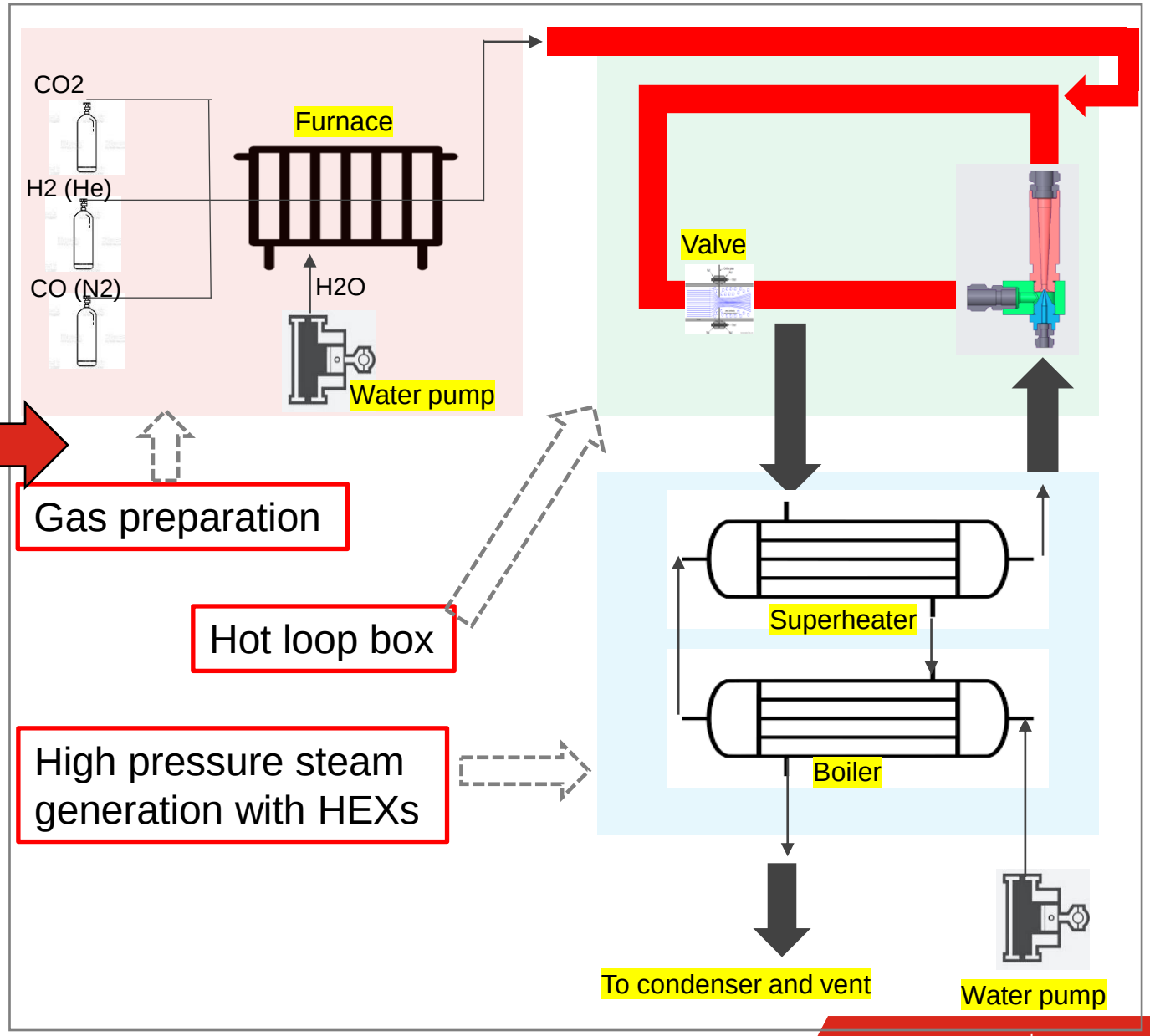
    * As of December 31, 2022

- Project extended 6 months to complete hot loop ejector testing

Task	Milestone	Planned Completion Date	Verification Method
2.0	M1: System Model Validated (TRL 3)	6/30/2021	System model calibrated to Baseline stack performance within 10% accuracy
3.0	M2: Cell Model Validated	9/30/2021	Cell model validated with Baseline stack data
4.0	M3: Steam Ejector Lab Tested (TRL 4)	11/30/2021	Steam Ejector demonstrated in lab test. Measure pressure, temperature, and flow rate
5.0	M4: Cell Substrate Design Finalized	3/30/2022	Cell Substrate design optimized based on the cell performance model results
5.0	M5: Make an Advanced Cell Substrate Prototype	6/30/2022	Demonstrate • Mass manufacture forming • Low cost joining • Robustness
6.0	M6: Steam Ejector Tested in Relevant Environment (TRL 5)	03/15/2023	Measure performance of the steam ejector in the hot test loop and compare with simulations. Measure pressure, temperature, gas composition, HX effectiveness and flow rate

Steam Ejector Loop Demonstration

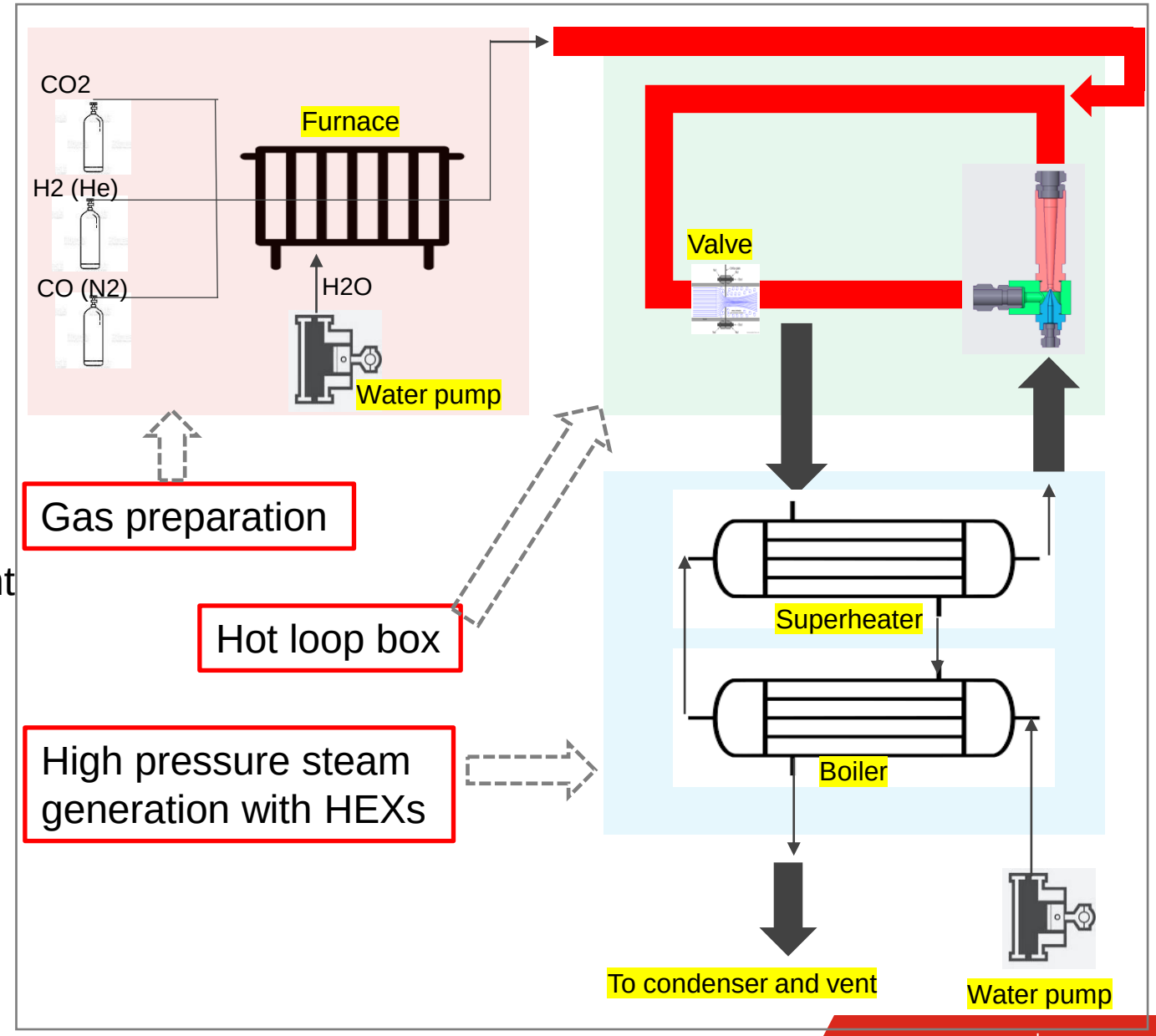




SOFC = Solid Oxide Fuel Cell
SOEC = Solid Oxide Electrolysis Cell

Steam Ejector Loop Demonstration

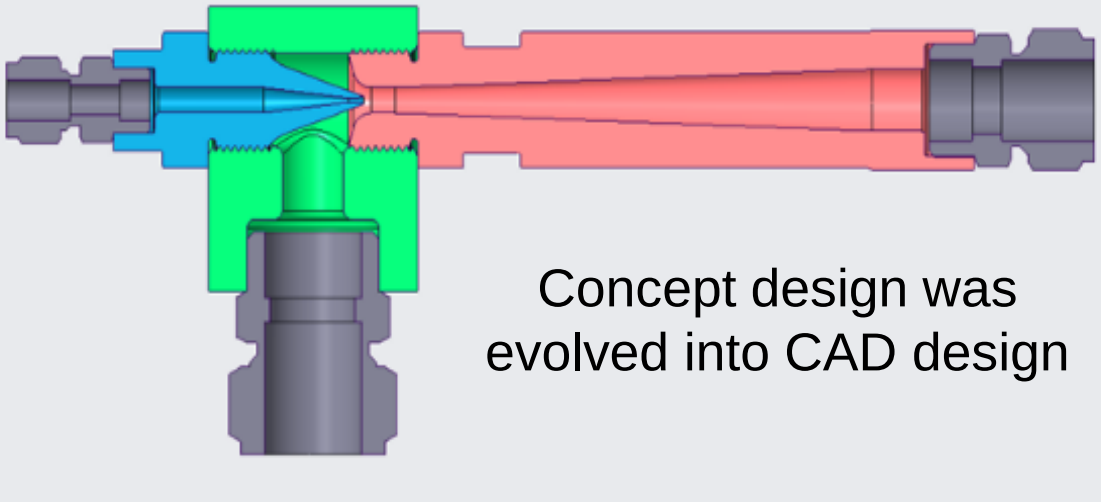
- **Objective**
  - From SOPO: “advance the steam ejector TRL by testing in a relevant environment … using realistic gas compositions and temperatures”
  - Advance to TRL 5
- **In Scope**
  - Test ejector with steam generation components
  - High temperature steam/H_2/CO_2/CO (SOFC) or steam/H_2 (SOEC)
  - Relevant SOFC & SOEC operation environment
  - Verify ejector performance and CFD model for high temperature steam operation
  - Impact of ejector on total system cost
- **Out of Scope**
  - Testing with full R-SOFC system – no stack, reformer, air side components
  - Ejector durability – long range testing



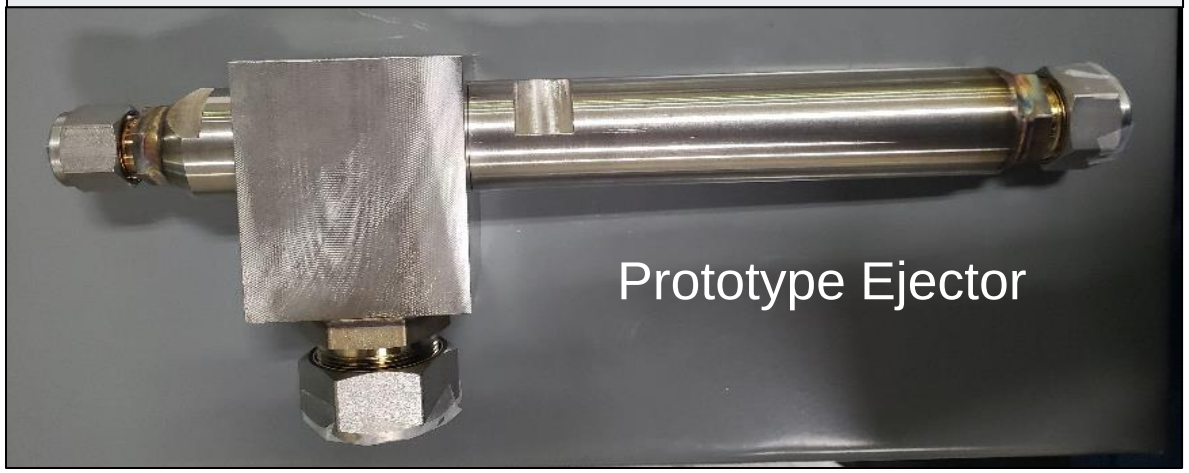
SOPO = Statement of Project Objectives

SOFC = Solid Oxide Fuel Cell
SOEC = Solid Oxide Electrolysis Cell

Ejector Design

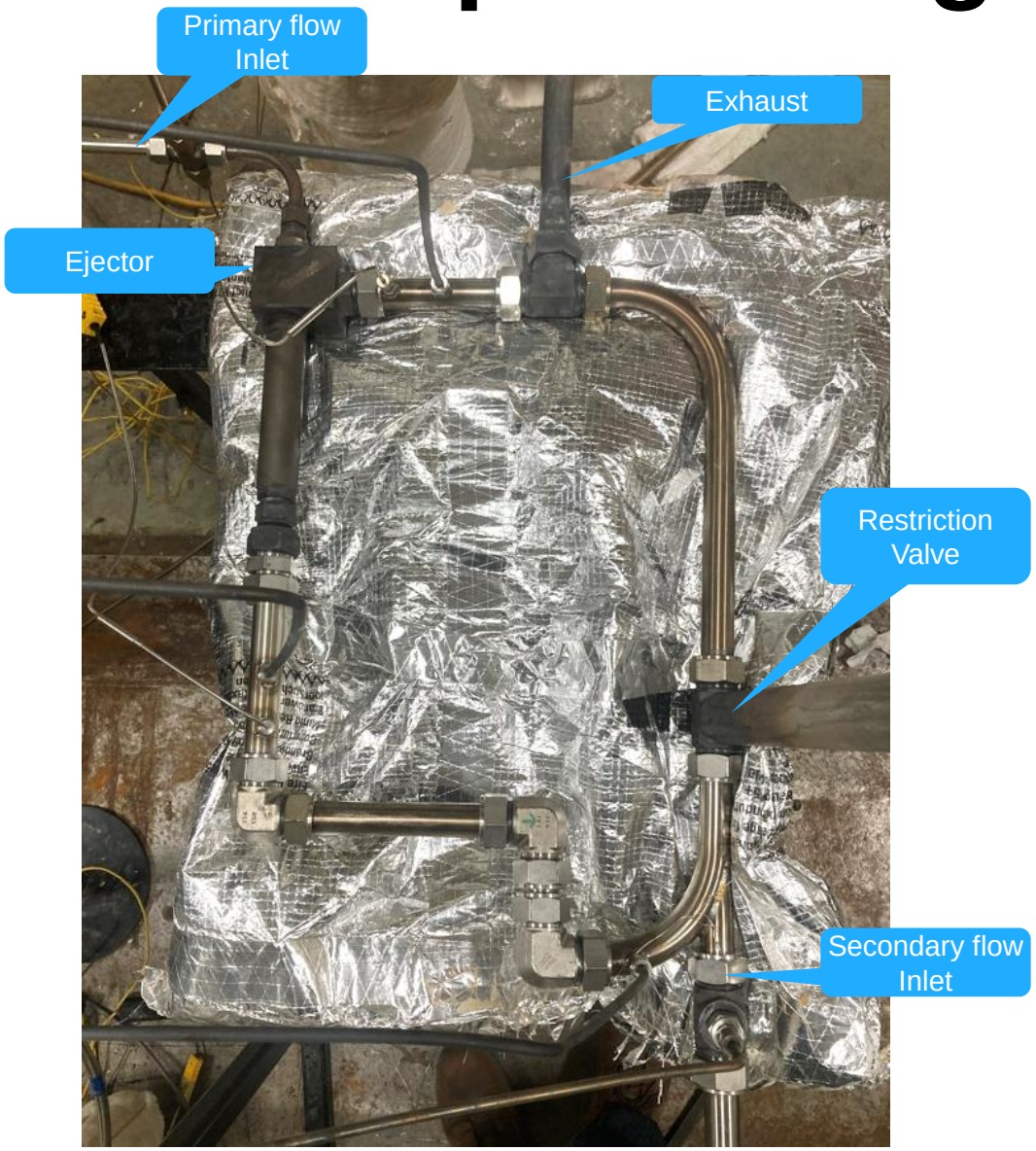


Concept design was evolved into CAD design



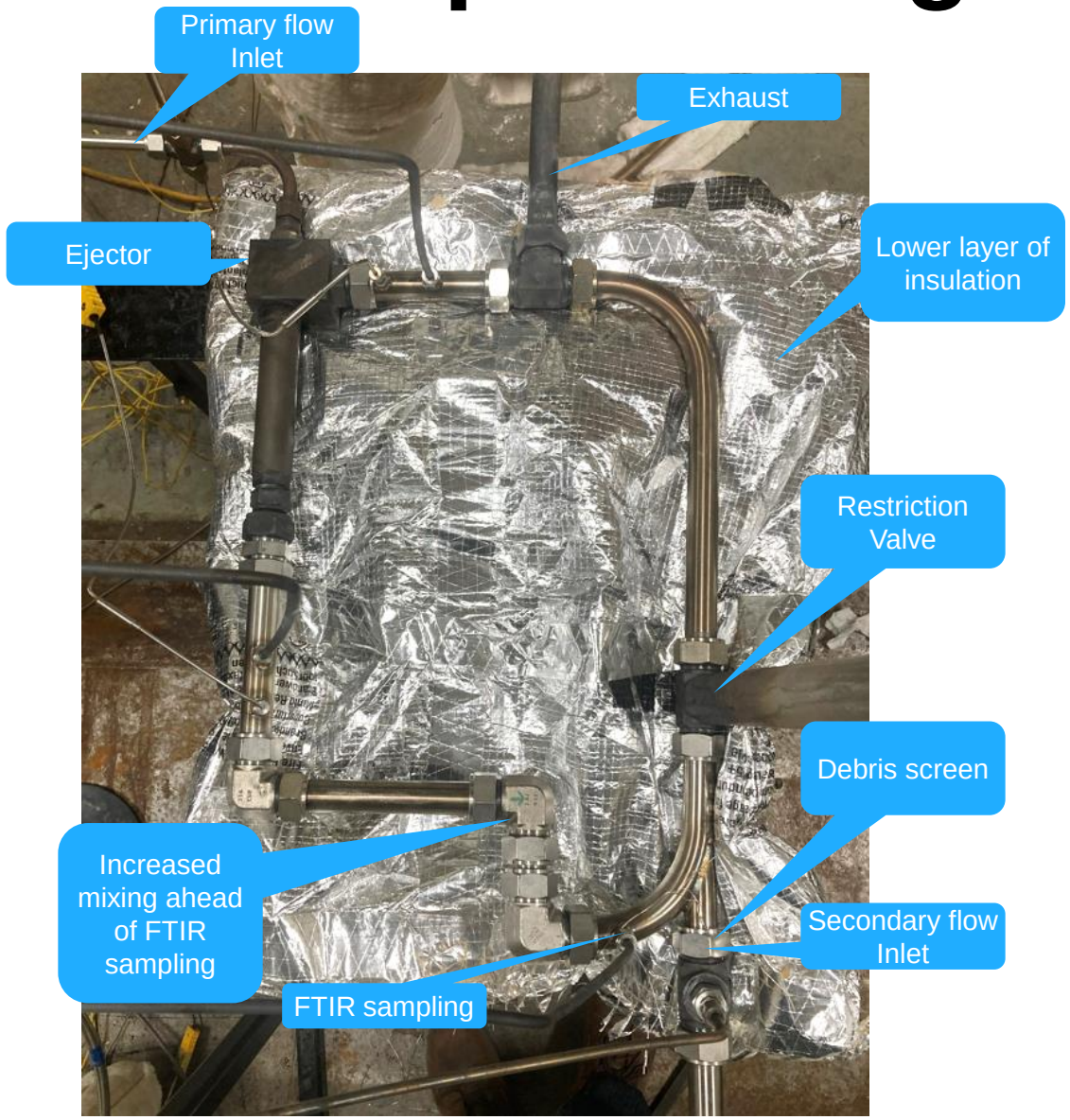
Prototype Ejector

Hot Loop Test Rig



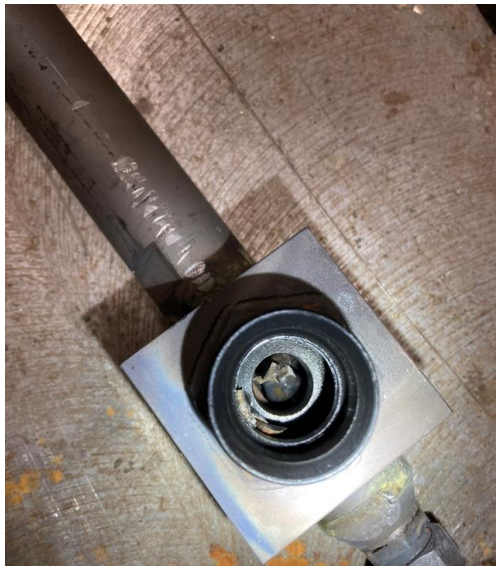
Fully insulated hot loop

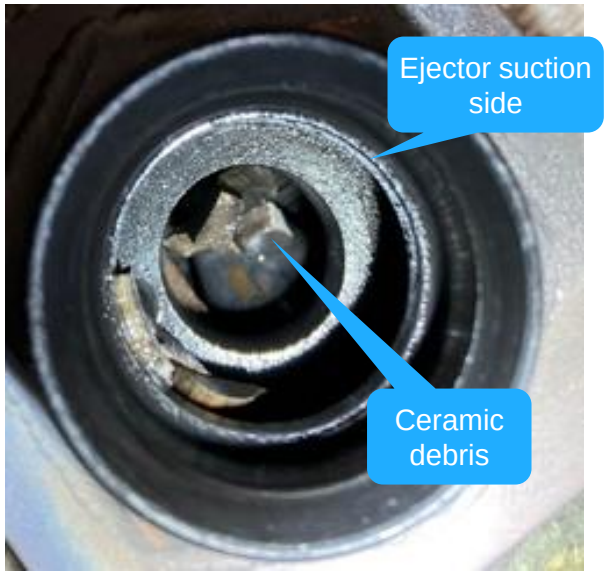
Hot Loop Test Rig Design



- Close-coupled high-temp insulation to maintain high temperature seen in ‘hot box’
- Secondary flow not measured, calculated from mass balance
- Entrainment ratio thus influenced by system variability
- To increase mixing opportunity between ejector outlet and FTIR sample location:
  - Increased number of 90^{o} bends
  - Mixer inserted in plumbing to aid mixing
  - FTIR located downstream of mixing aids

Ejector Performance Degradation

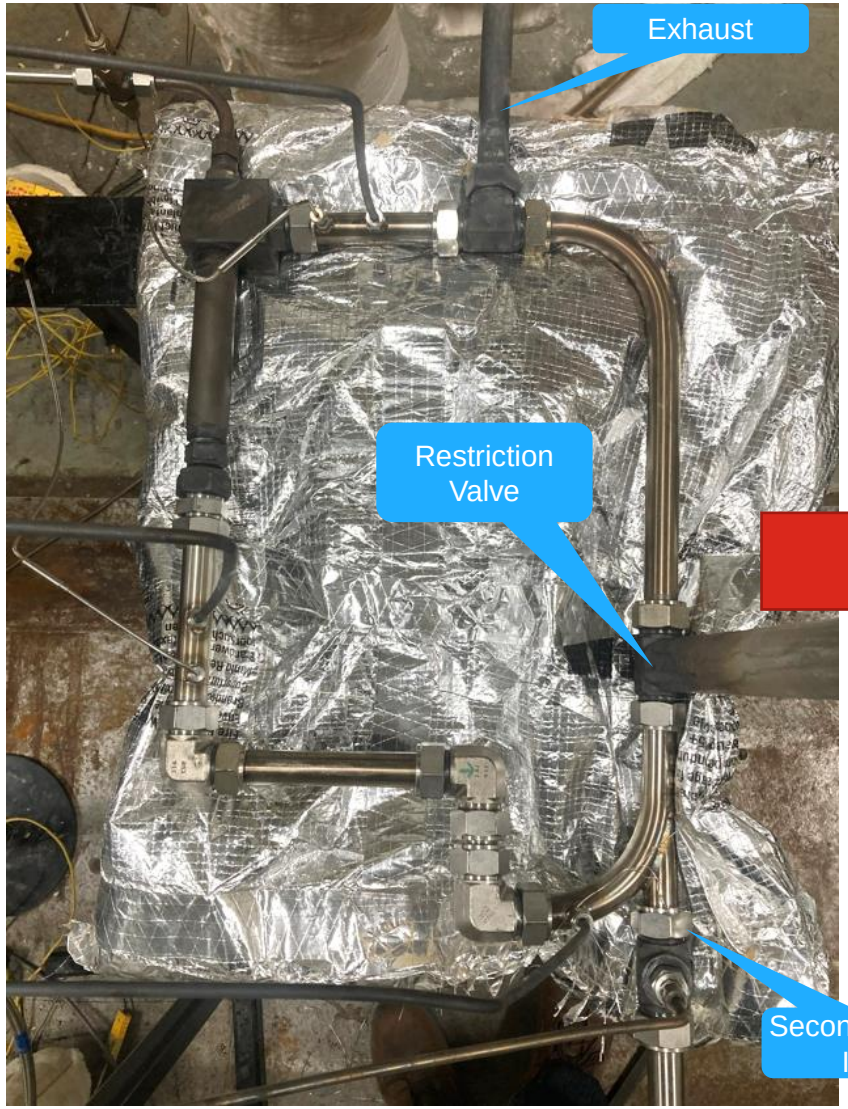


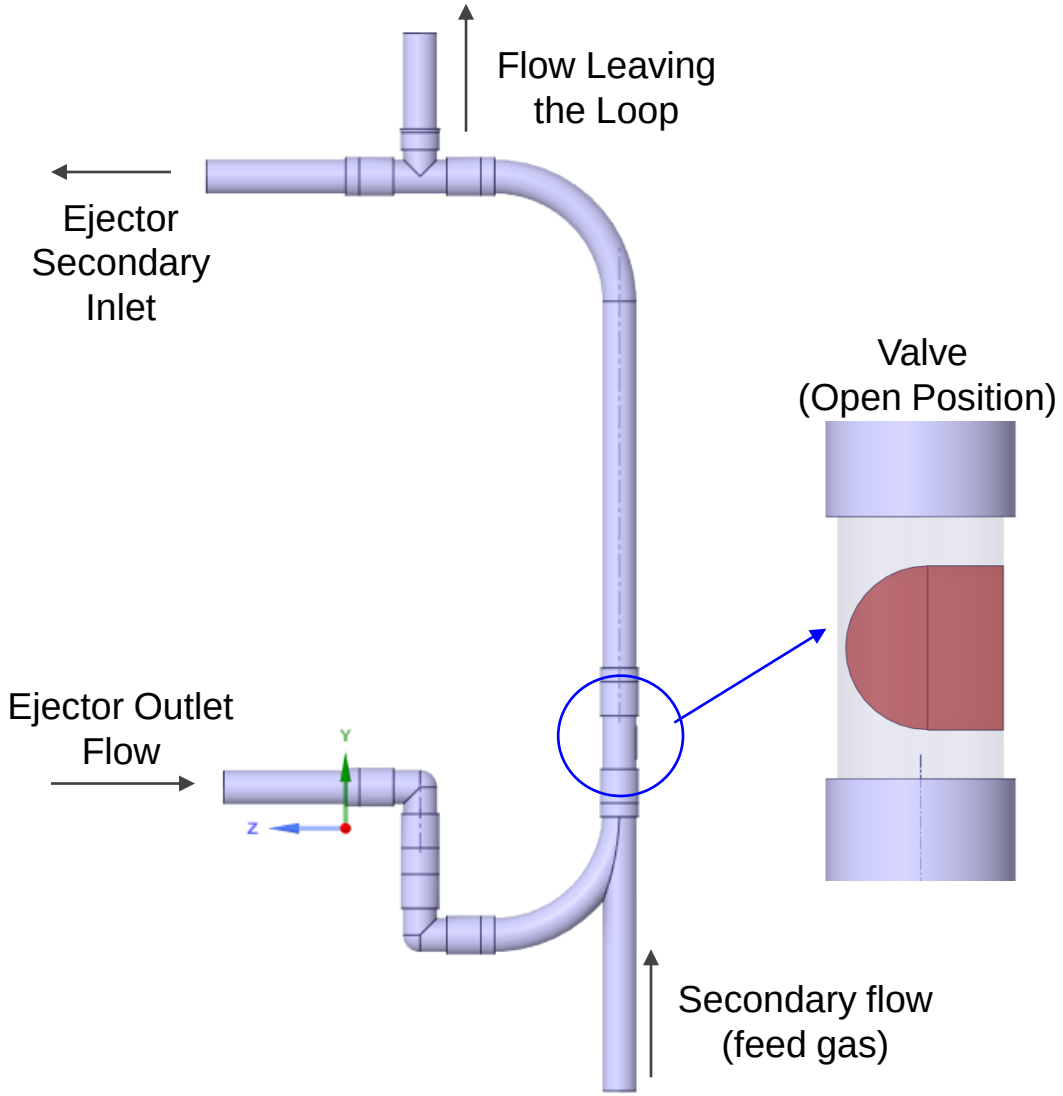


- Debris found inside ejector suction side causing restriction and flow disturbance
  - Debris originated from electric superheater
  - Ceramic within electric superheater had cracked and several pieces had traveled downstream
- Ceramic debris removed and ejector re-installed
- Screen added to prevent any future debris from entering hot loop

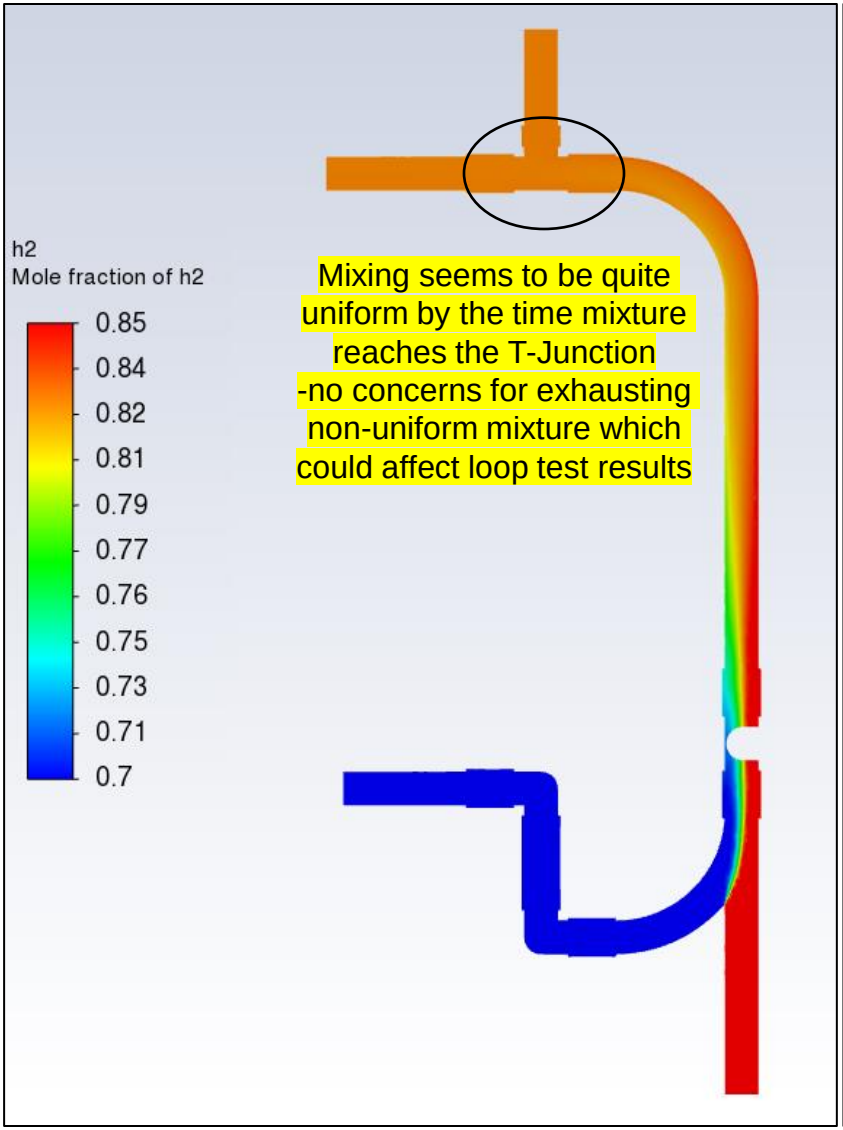
Hot Loop Modeling

Hot Loop plumbing is modeled in a CFD model to verify the mixing quality of ejector flow and feed gas

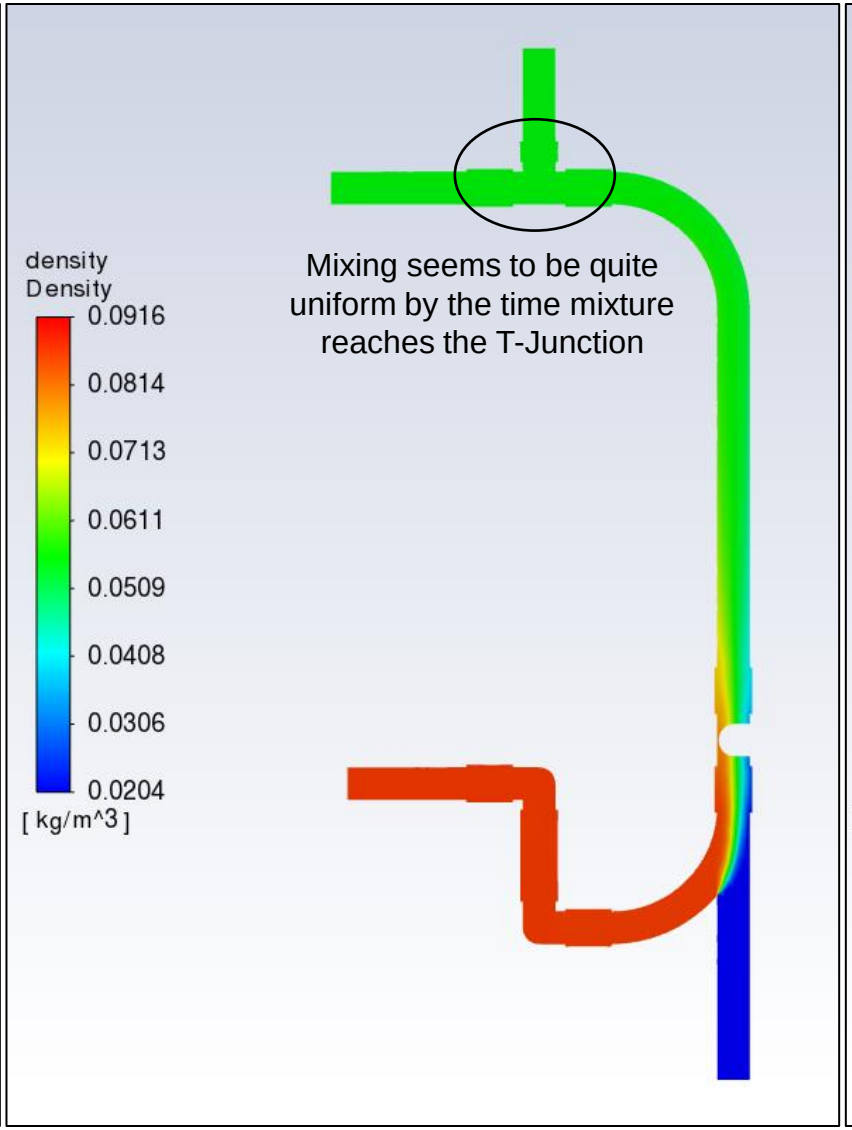




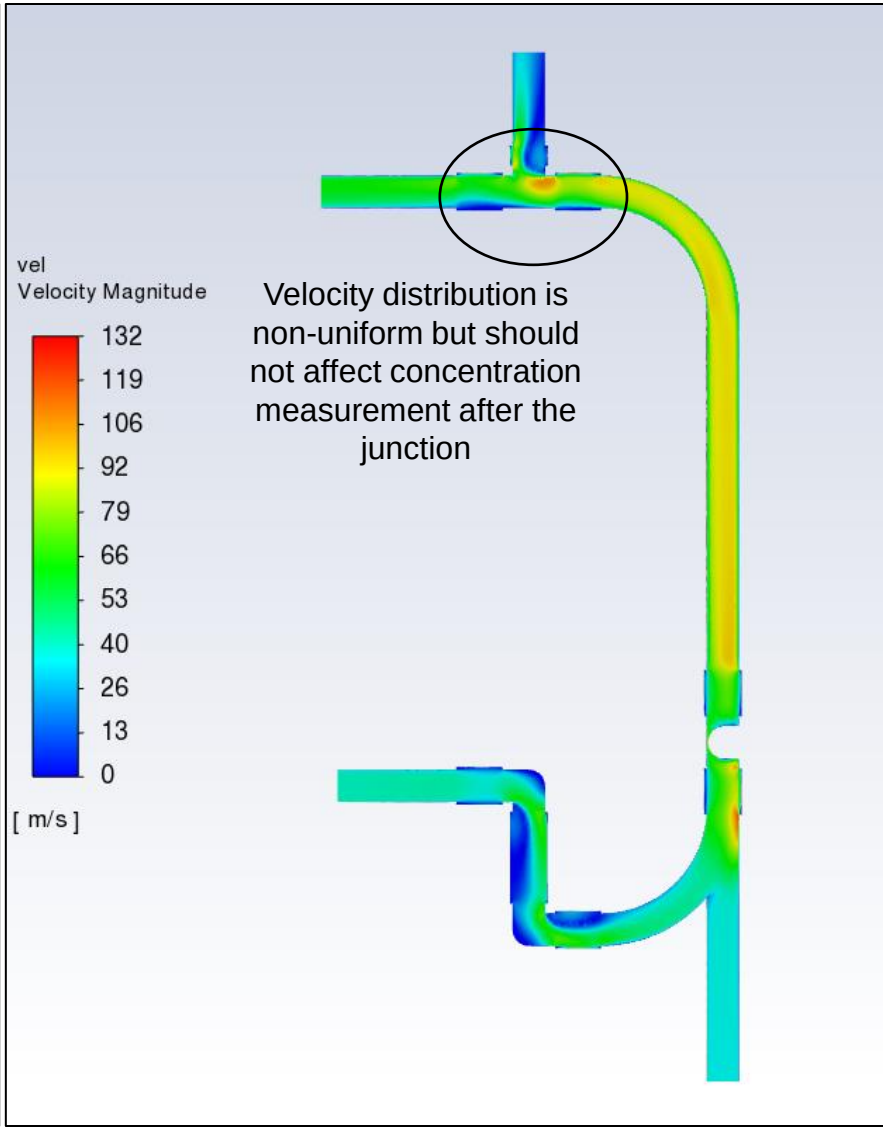
SOEC Operating Point



Mixing seems to be quite uniform by the time mixture reaches the T-Junction
-no concerns for exhausting non-uniform mixture which could affect loop test results



Mixing seems to be quite uniform by the time mixture reaches the T-Junction

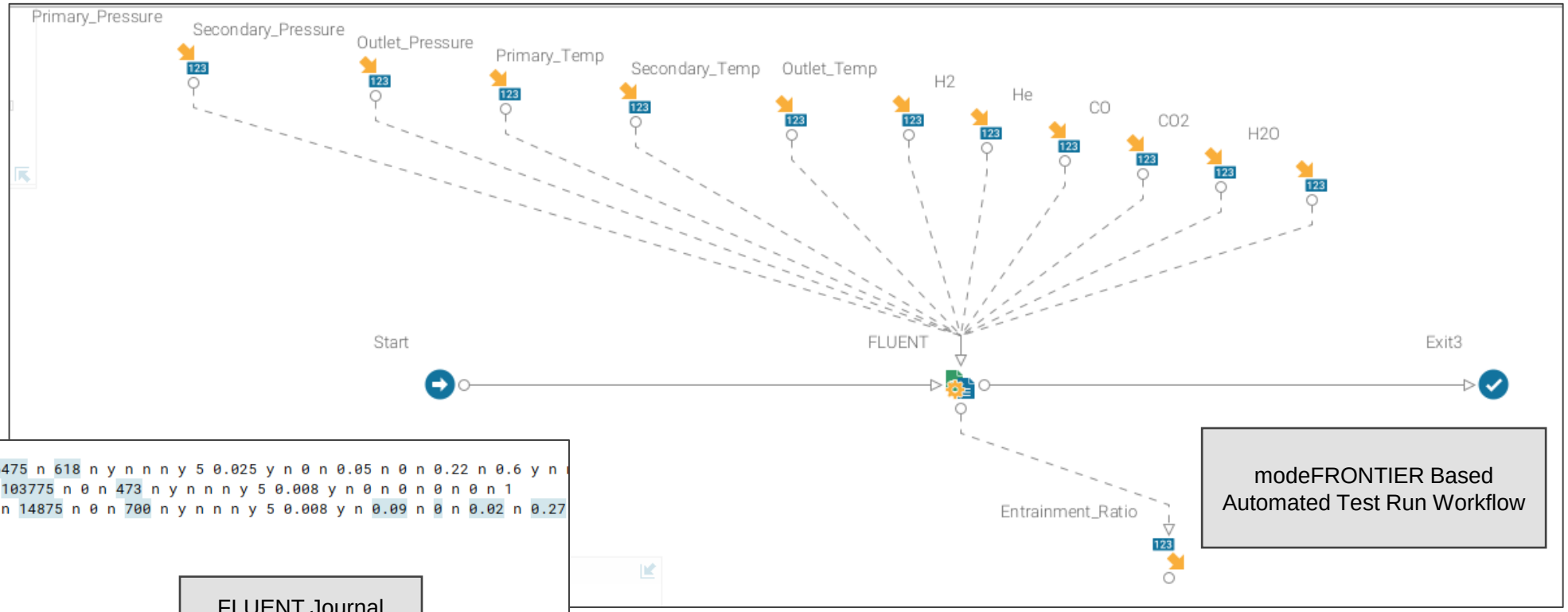


Velocity distribution is non-uniform but should not affect concentration measurement after the junction

CFD Process Upgrade

- CFD Workflow is fully automated to launch the CFD runs specific to the test data-sets
- This upgrade has helped in improving engineering efficiency by significant margin

	Manual Job Submission	Automated Job Submission
Engineering time to launch 25 test data-points & process the results (This is not the CFD job run-time)	15 hours	1 hour



Test data points are read into modeFRONTIER and FLUENT Journal script is updated for individual runs

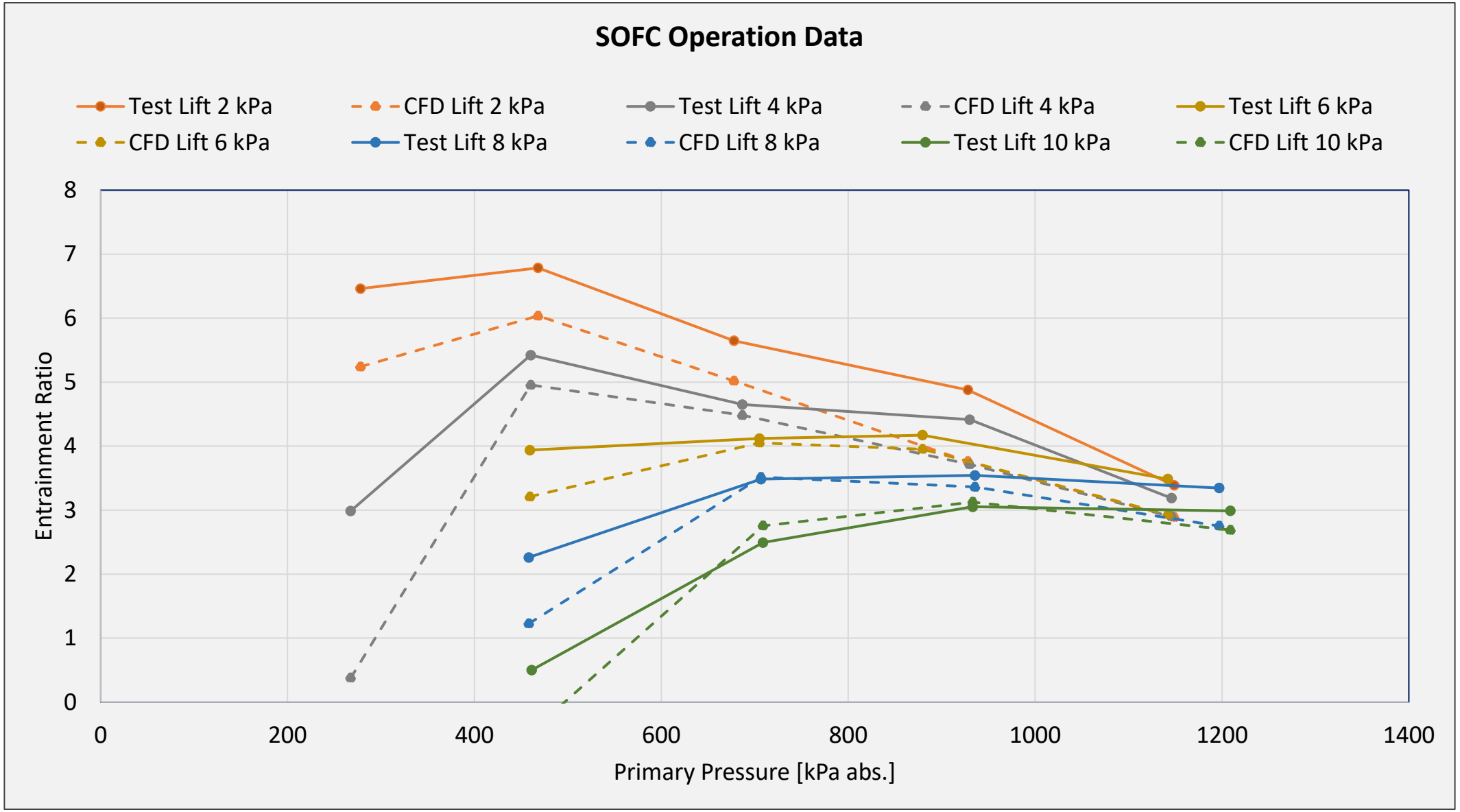
```
file rc hotloop_2kPa
define bc press-out pressure-outlet y n 16475 n 618 n y n n n y 5 0.025 y n 0 n 0.05 n 0 n 0.22 n 0.6 y n
define bc pi primary-pressure-inlet yes n 103775 n 0 n 473 n y n n n y 5 0.008 y n 0 n 0 n 0 n 0 n 1
define bc pi secondary-pressure-inlet yes n 14875 n 0 n 700 n y n n n y 5 0.008 y n 0.09 n 0 n 0.02 n 0.27
solve mon res cc n n n n n n n n n n n n
solve init cd az
solve init if
solve init fmg yes
solve it 1500
file wcd it1500
report flux mass no 2 3 () yes mass_flow_pp100kpa.out
```

FLUENT Journal

modeFRONTIER Based Automated Test Run Workflow

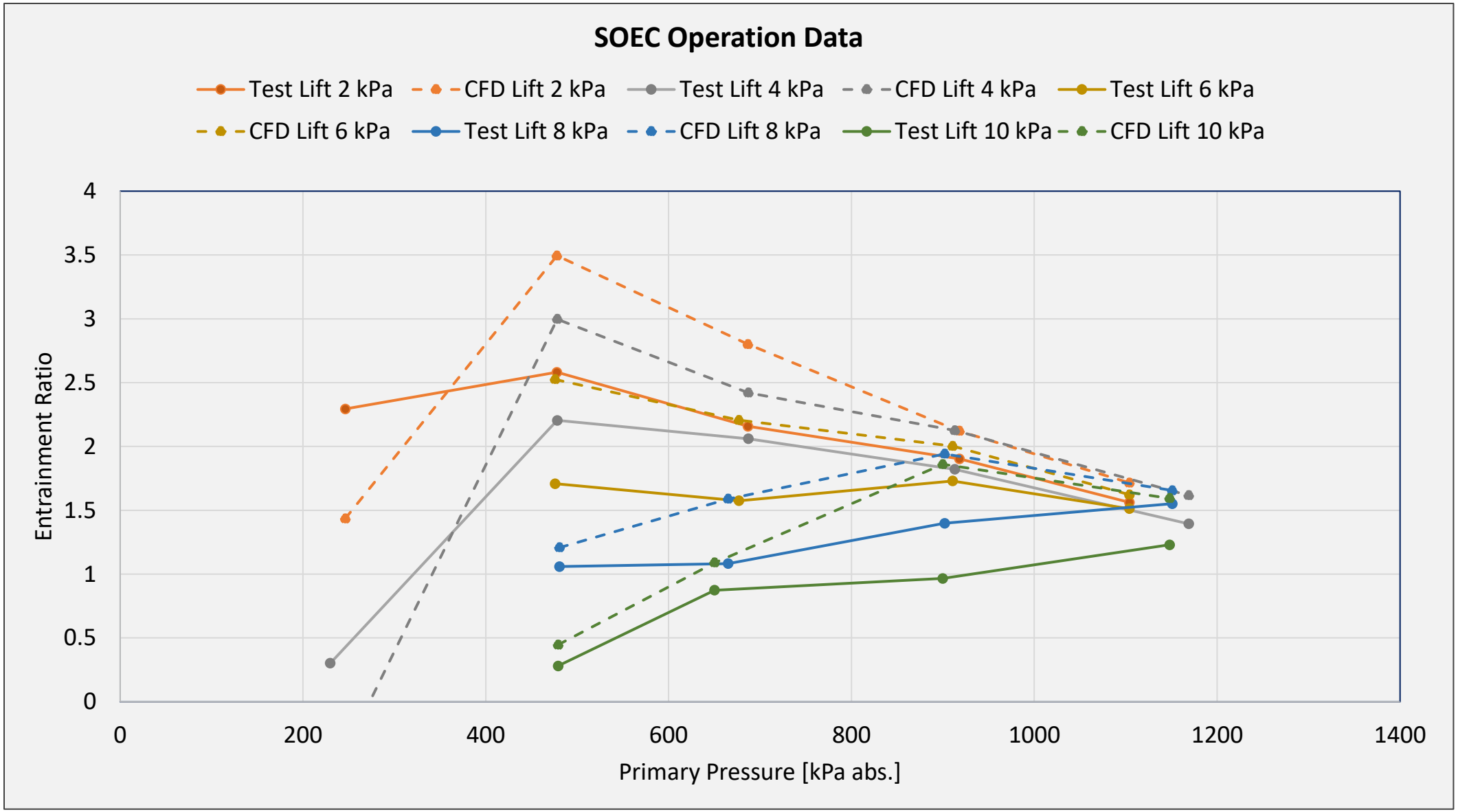
CFD vs Test: SOFC Mode

There is a good match between CFD predictions and test data



CFD vs Test: SOEC Mode

Qualitative trends are correctly captured . Quantitative differences are relatively higher as compared to SOFC mode



Project Next Steps

- Remaining Budget Period 2 Tasks:
  - Task 7.0: Techno-economic Analysis (TEA)
- Complete project June 30, 2023
- Close out tasks in Q3 2023:
  - Submit TEA
  - Submit Final Project Report

Acknowledgements

- US DOE for financial support under Award number DE-FE0031971
- Mr. Drew O’Connell for his guidance as Program Manager
- Cummins thermal recovery team for design, build and operation of ejector hot loop test rig
- CFD analysis team for design of ejector concept and analysis of ejector hot loop test results

Q+A


Cummins