

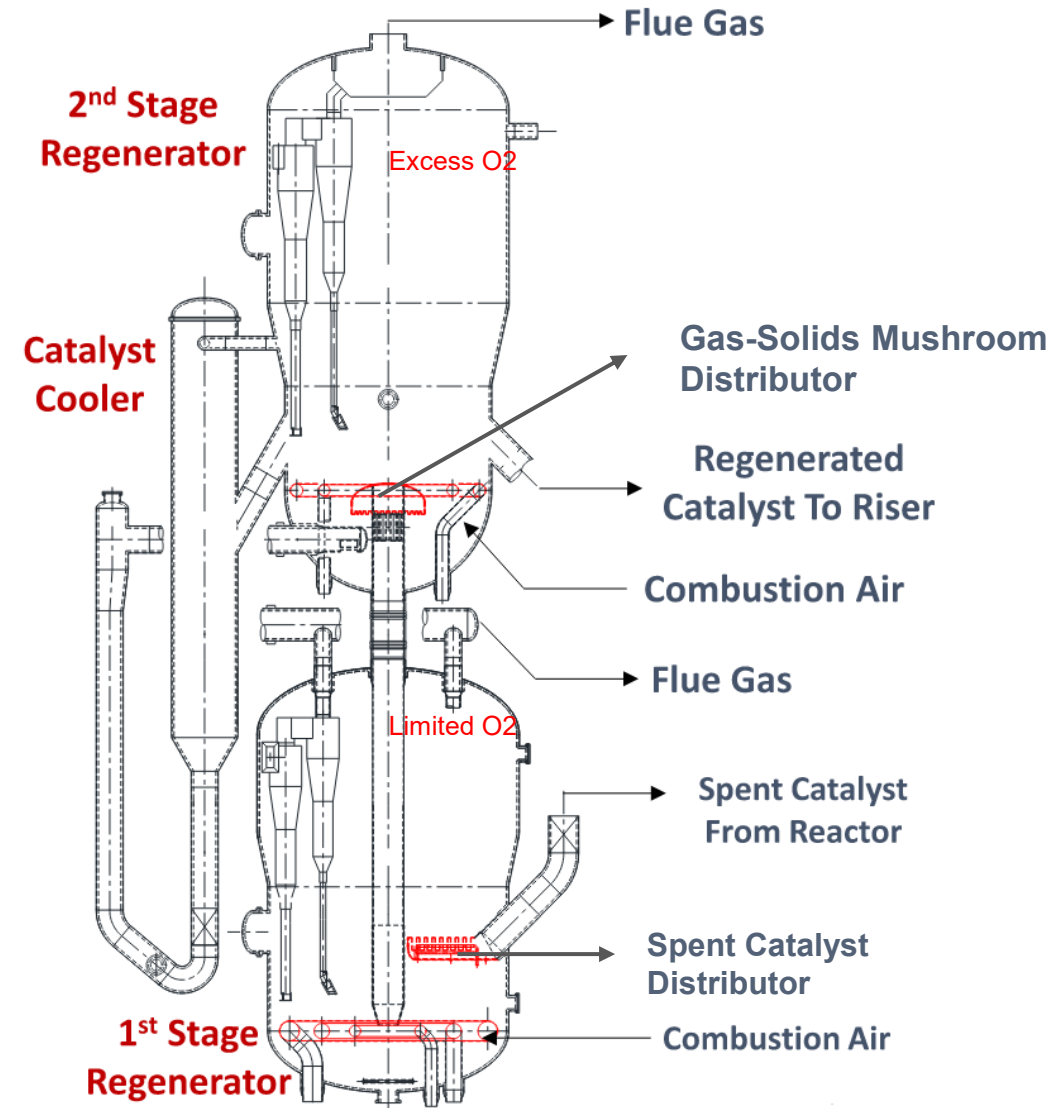
# CFD Evaluation of Spent Catalyst Distributor Enhancements in RFCC Regenerators

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# RFCCU Regenerator Configuration

The RFCC unit operates with a two-stage regenerator system

- Stage 1 – Partial Burn Regenerator
  - Operates under partial combustion conditions. Minimizes catalyst deactivation
- Stage 2 – Full Burn Regenerator
  - Operates with excess oxygen (full combustion) Completes coke burn-off
- Catalyst Transfer System
  - Catalyst is transported from Stage 1 to Stage 2 via the lift line. Spent catalyst and lift air are distributed into Stage 2 through the mushroom distributor
- Regenerated Catalyst Handling
  - Recovered through withdrawal wells. Returned to the riser



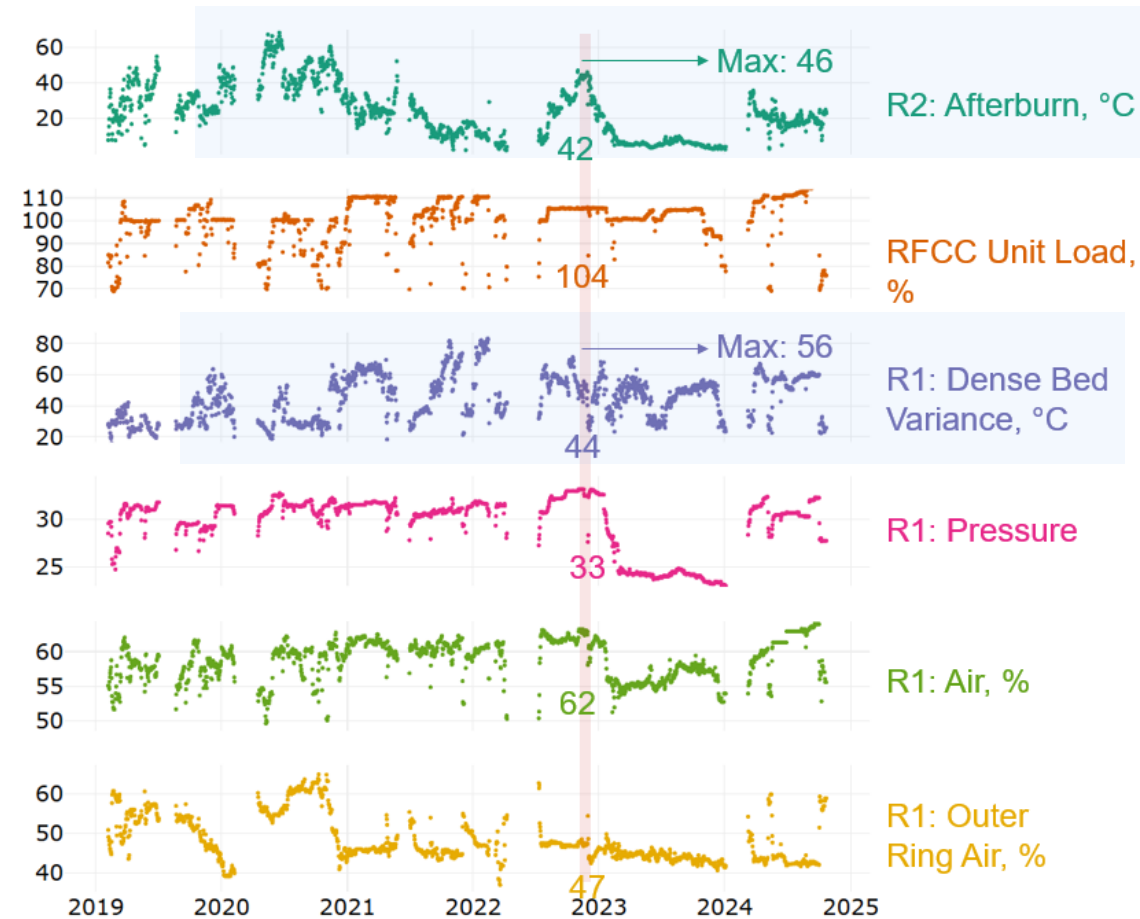
# Problem Statement

- A commercial Resid Fluid Catalytic Cracking (RFCC) unit has been in operation since 2016.

## Key Challenges include:

- Temperature maldistribution in Regenerator 1
  - Non-uniform dense bed temperature profile - Likely caused by maldistribution of spent catalyst
- Afterburn in Regenerator 2
  - Afterburn ( $>40^{\circ}\text{C}$ ), indicating post-combustion of CO in the dilute phase

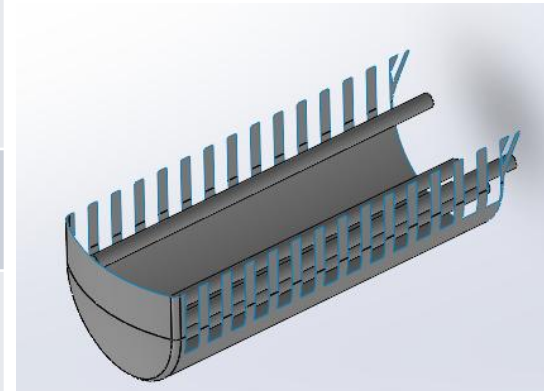
To investigate the issue and potential design improvements, CFD modeling was conducted separately for both regenerators



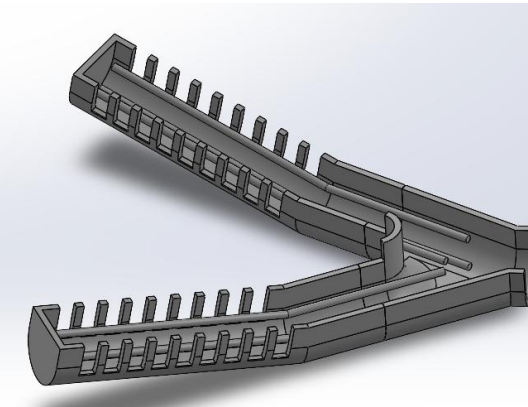
# Modeling Objective and Study Cases

Aspect	Regenerator 1
Objective	Improve catalyst distribution & temperature uniformity
Base Case	Existing distributor : Assess distribution & temperature
Modified Case	Wye bathtub distributor Improve uniformity
Key Metrics	<ul style="list-style-type: none"><li>• Distribution of carbon mass fraction from SCSP</li><li>• Radial and sectoral temperature distribution</li></ul>

Existing distributor

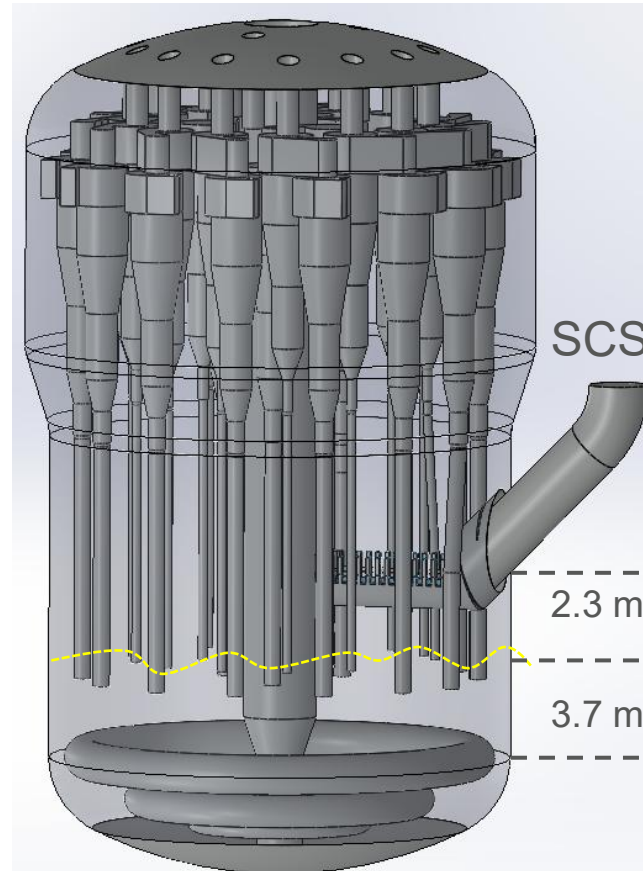


T.EN Compound Wye Bathtub

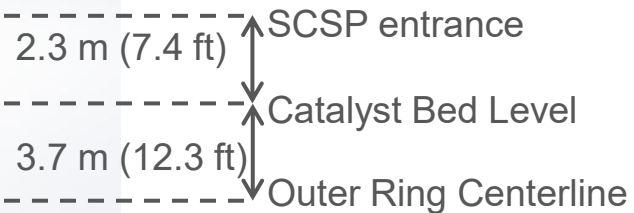


# Existing Regenerator 1 Configuration

- SCSP enters ~2.3 m (7.4 ft) above bed
- Bed level: ~3.7 m (12.3 ft) above BTL
- Partial burn, turbulent regime, 17 cyclones
- Air via 4 ring distributors
- Catalyst exits via plug valve through the lift line



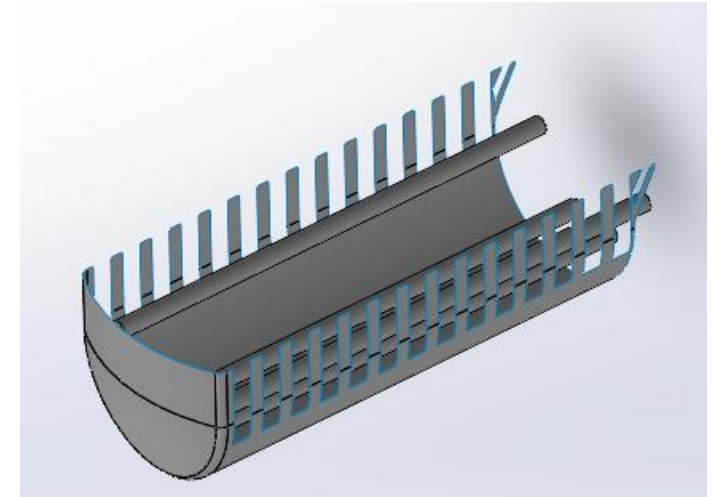
Equipment / Parameter	Case1	Case2	Notes
Top (dilute) section ID lining	~16 m (53 ft)	~16 m (53 ft)	ID
Bottom (dense) section ID lining	~14 m (46 ft)	~14 m (46 ft)	ID
Bathtub type	Existing T.EN bathtub	New T.EN Wye bathtub	Existing: 1 arm New: 2 arms, sloped
Bathtub Spargers (BT)	4	6	Total spargers for bathtub distributor
Total flow through Spargers	3219 kg/h (5113 lb/h)	13406 kg/h (29555 lb/h)	kg/h flow



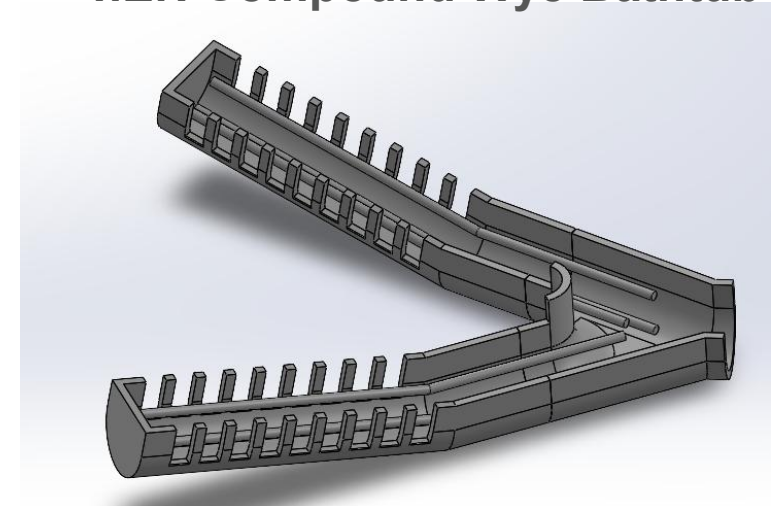
# Regenerator 1 – Key design changes

Parameter	Case 1 (Base)	Case 2 (Modified)
Distributor Type	Single-arm bathtub distributor	T.EN Compound Wye bathtub (2 arms, sloped)
Number of Spargers	4	6 (3 per arm)
Sparger Flow Rate	~3,219 kg/h	~13,406 kg/h

Existing distributor



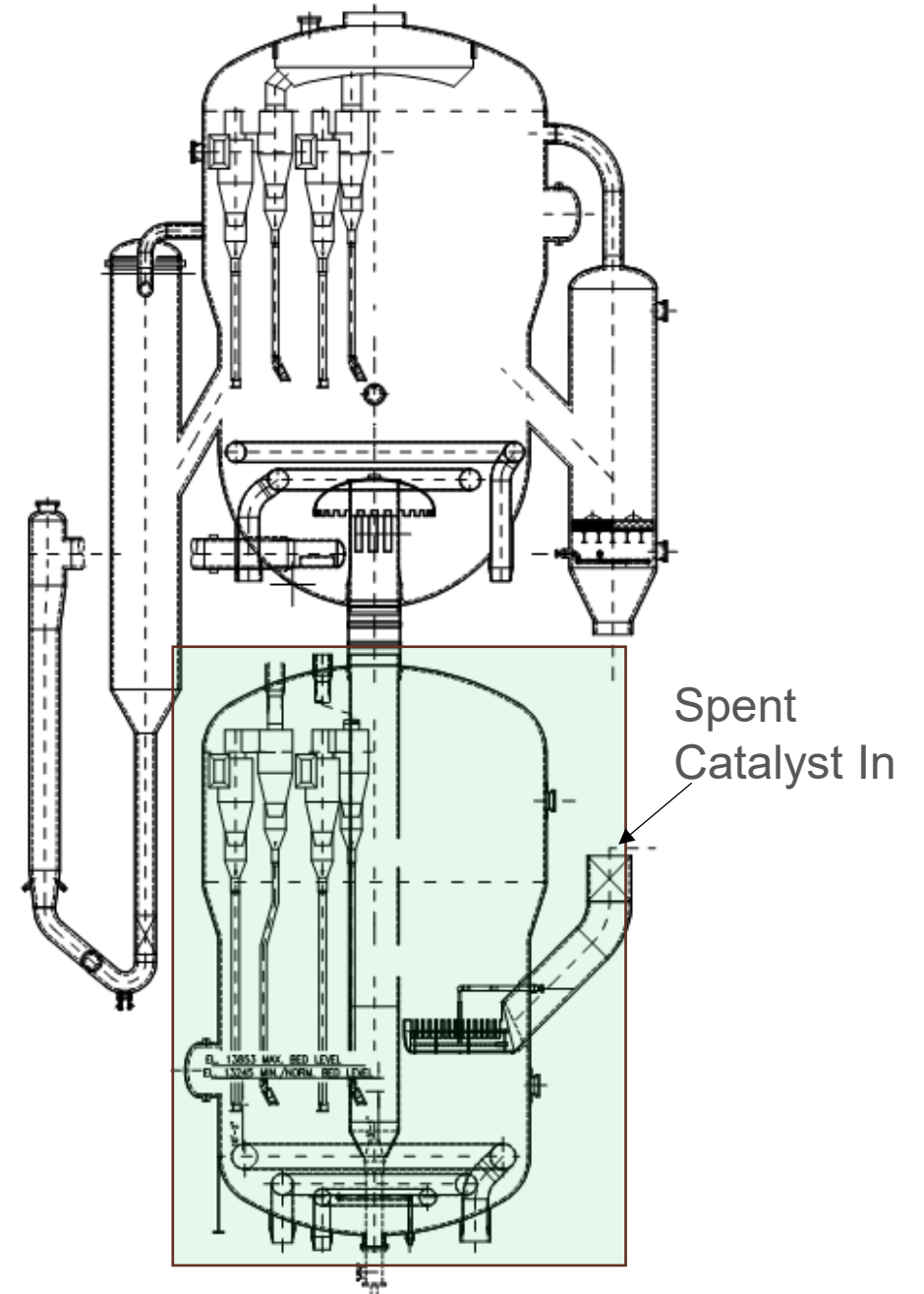
T.EN Compound Wye Bathtub



# Modeling domain

## Regenerator 1

- Portion of spent catalyst standpipe up to regenerator inlet
- Bathtub distributor (Case 1: original, Case 2: Wye)
- 4 Air rings: Plug valve fluffing, inner, middle, and outer
- External geometries of Cyclones, Lift line and Air rings were subtracted from the model



# Assumptions

## Cyclones

- Cyclones/diplegs excluded; flow not modeled
- Pressure BCs at cyclone inlets; flow BCs at diplegs
- 100% efficiency assumed (99% primary, 1% secondary)

## Hydrodynamics & Kinetics

- Coupled hydrodynamics + kinetics
- Coke combustion via T.EN model
- Simulated to ~60 s steady state

## Computational Grid

- ~3 million cells in Regenerator

## Air Injection BCs

- Air injected through discrete nozzle BCs at actual locations/orientations
- Applied to all relevant air rings and fluffing rings in Regenerator 1
- Jet velocity and momentum maintained per design intent

# Coke Combustion Kinetics

- Spent catalyst from the stripper consists predominantly of
  - Catalyst Inerts (~99%),
  - Coke, typically represented as  $CH_xN_yS_z$  (carbon, hydrogen, nitrogen, and sulfur)
  - Entrained hydrocarbons, commonly referred to as volatiles. They could also be desorbed from catalyst pores or produced from Coke
- Three major classes of reactions occur in the regenerator:
  - Solid-phase coke combustion
  - Homogeneous gas-phase reactions
  - Catalytic gas-phase reactions
- The rate constants and kinetic expressions used to describe these reactions have been developed in collaboration with IFPEN, as part of the FCC Alliance

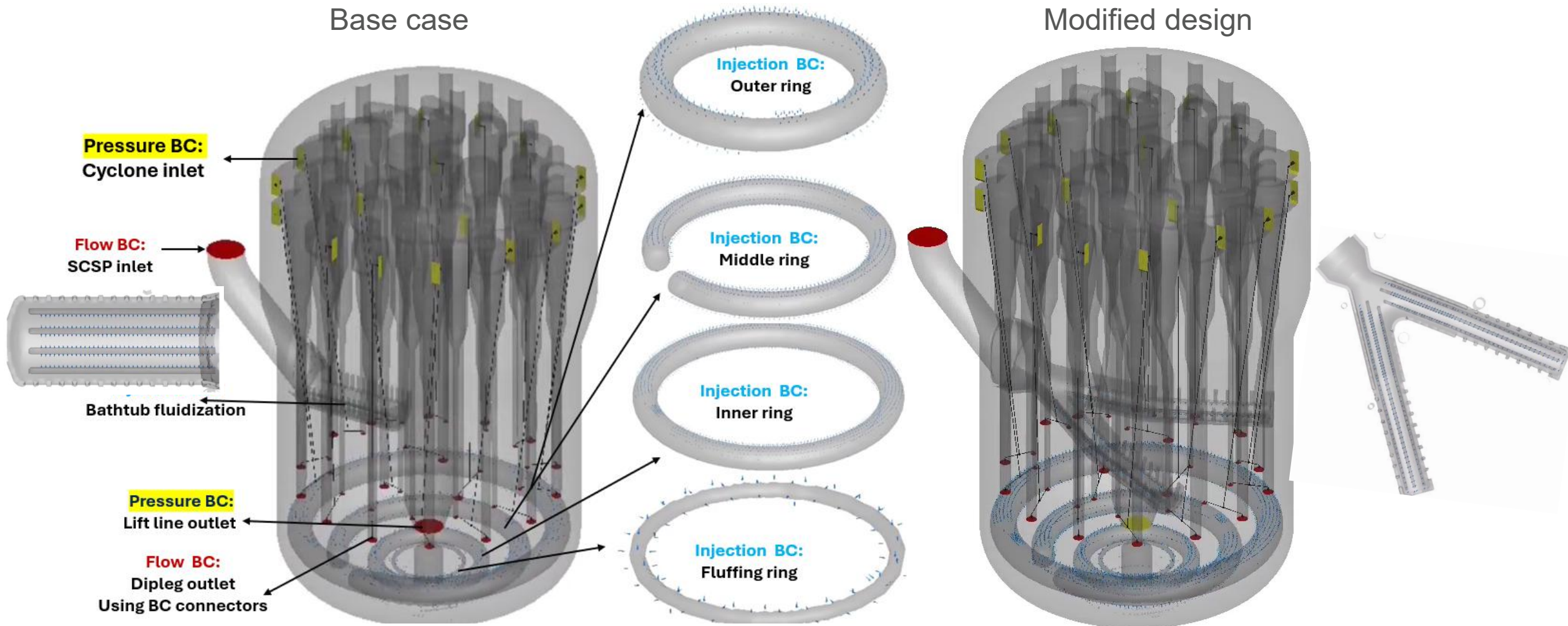
Solid phase reactions	Coke carbon combustion	$C_{\text{Coke}} + \frac{\mu + 1}{\mu + 1} O_2 = \frac{\mu}{\mu + 1} CO + \frac{1}{\mu + 1} CO_2$
	Coke hydrogen combustion	$H_{\text{Coke}} + 0.25O_2 = 0.5H_2O$
	Coke sulfur combustion	$S_{\text{Coke}} + O_2 = SO_2$
	Coke nitrogen combustion	$H_{\text{Coke}} + C_{\text{Coke}} + N_{\text{Coke}} = HCN$
Homogenous gas phase reactions	CO oxidation	$CO + 0.5O_2 = CO_2$
	HCN oxidation	$HCN + 1.75O_2 = NO + CO_2 + 0.5H_2O$
	Volatile $H_2$	$H_2 + 0.5O_2 = H_2O$
	Volatile $CH_4$	$CH_4 + 1.5O_2 = CO + 2H_2O$
	Volatile $C_2H_4$	$C_2H_4 + 2O_2 = 2CO + 2H_2O$
Catalytic gas phase reactions	CO oxidation	$CO + 0.5O_2 = CO_2$
	HCN oxidation	$HCN + 1.75O_2 = NO + CO_2 + 0.5H_2O$
	CO assisted NO reduction	$2NO + 2CO = N_2 + 2CO_2$
	NO reduction	$NO + 2C = N_2 + 2CO$

} Volatiles are burnt off in R1

# Regenerator 1: Boundary Conditions

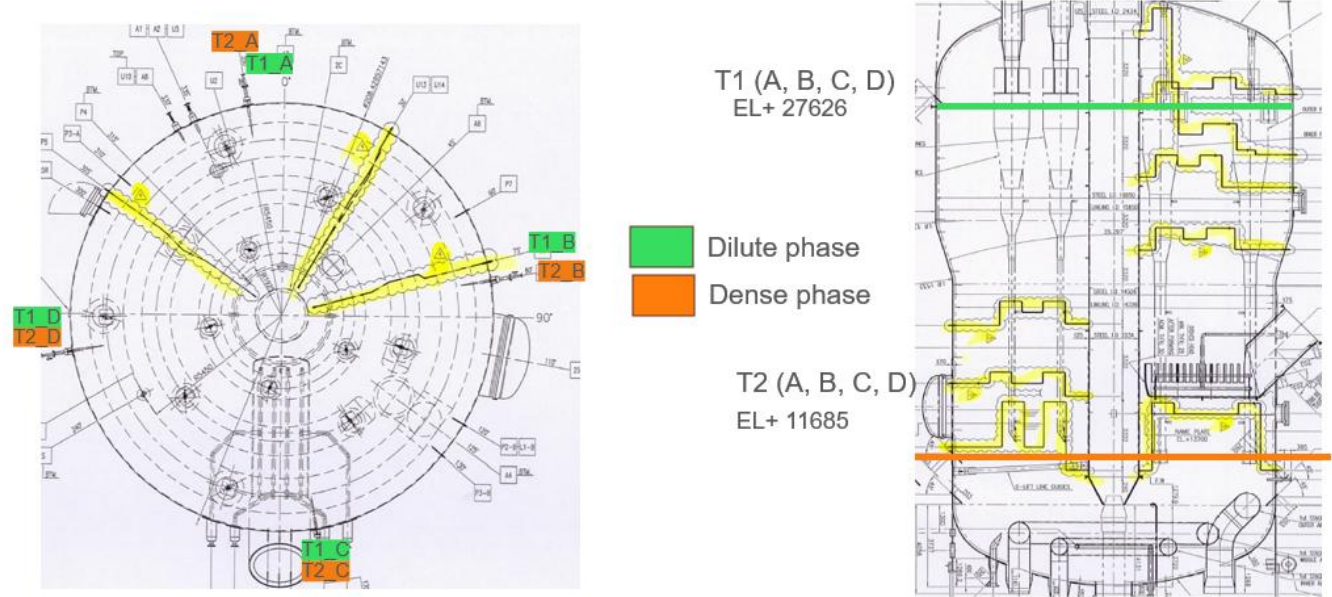
Base case

Modified design



# Baseline Simulations vs Plant Data: Transient Temperatures

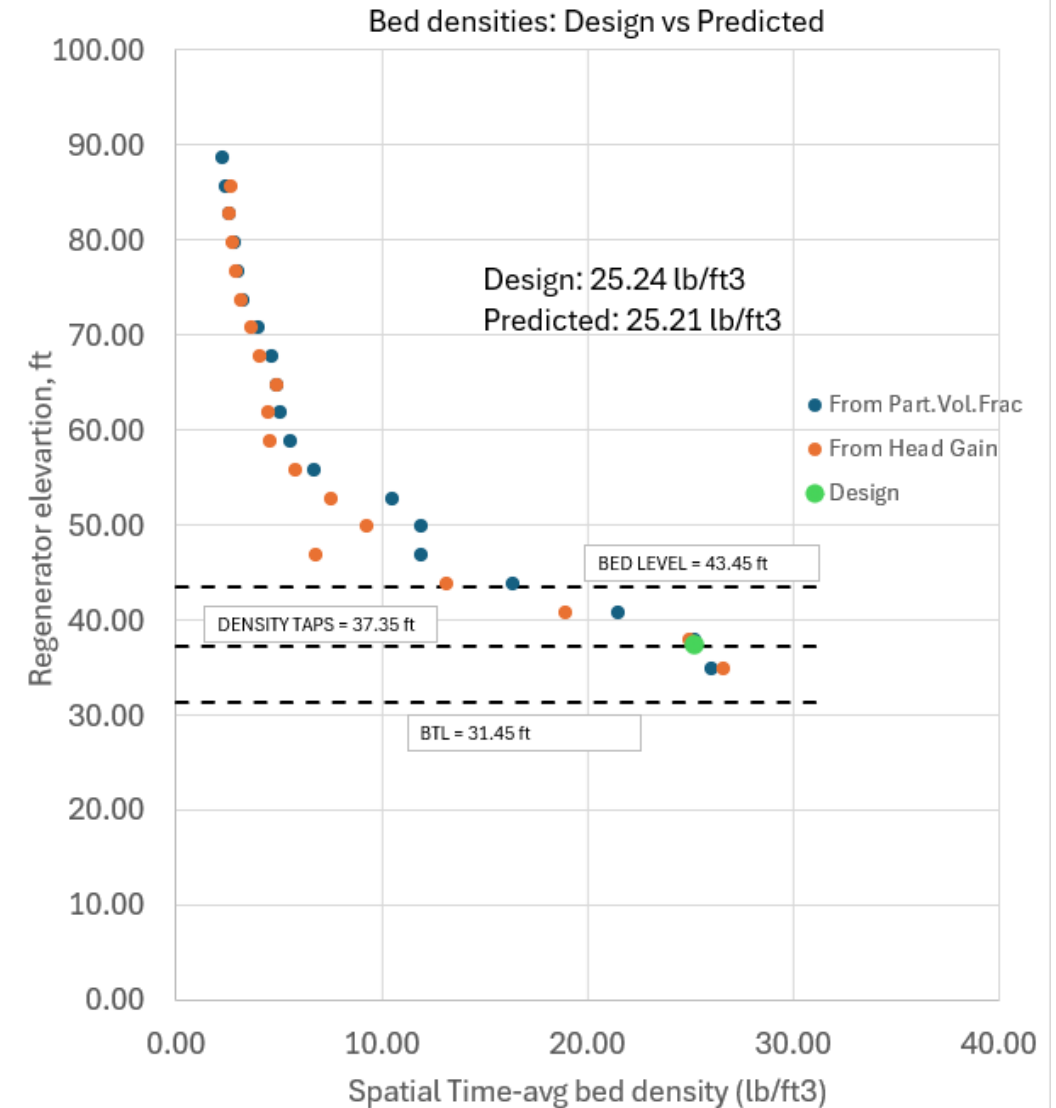
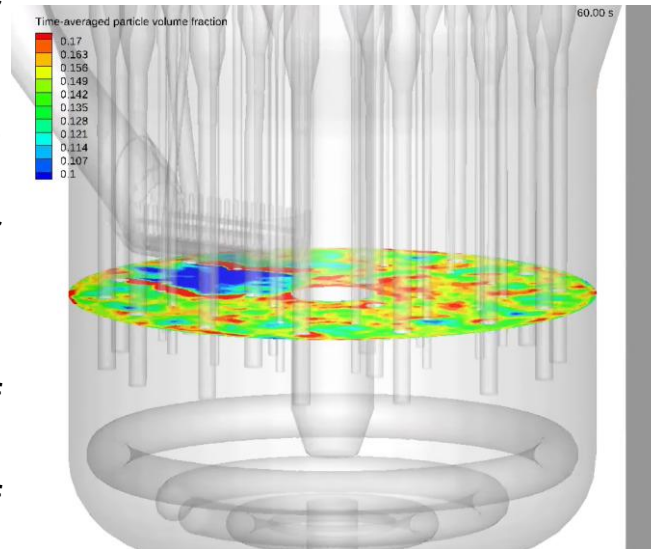
- Transient data points in the simulation were located in the dense and dilute phases of Regenerator 1, matching the actual unit for accurate comparison
- CFD-predicted dense phase temperatures closely match plant measurements
- Three dilute phase temps (T1A, T1C, T1D) agree well; T1B shows some discrepancy, likely due to local flow and modeling challenges
- T1A (dilute) and T2A (dense) are the hottest points, consistent in both simulation and plant data



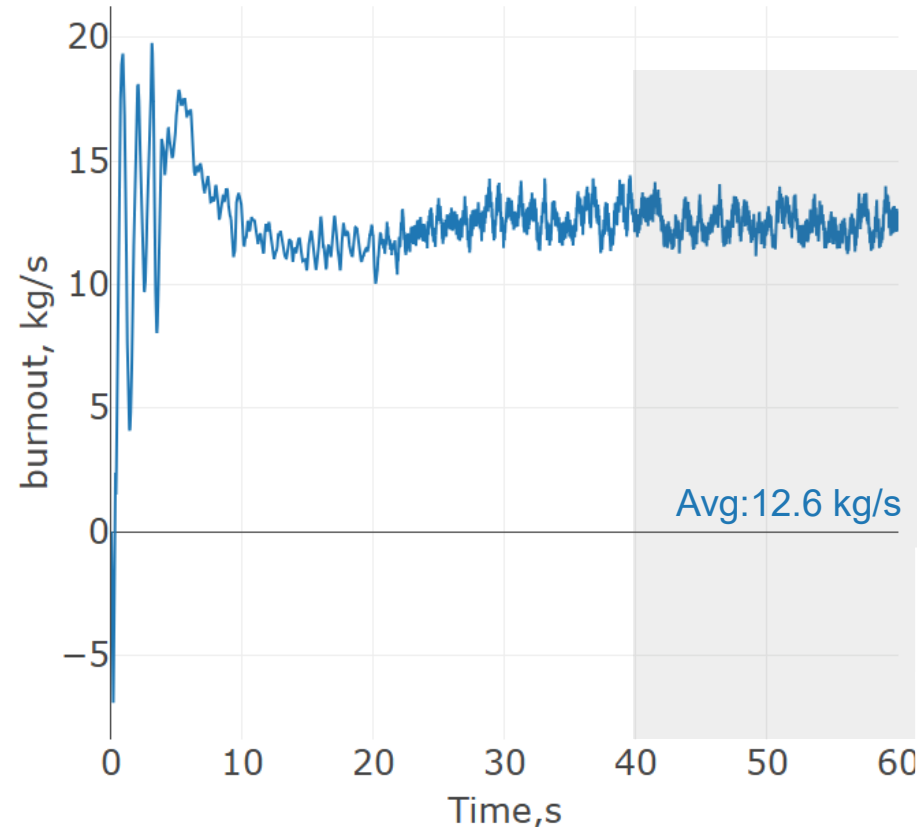
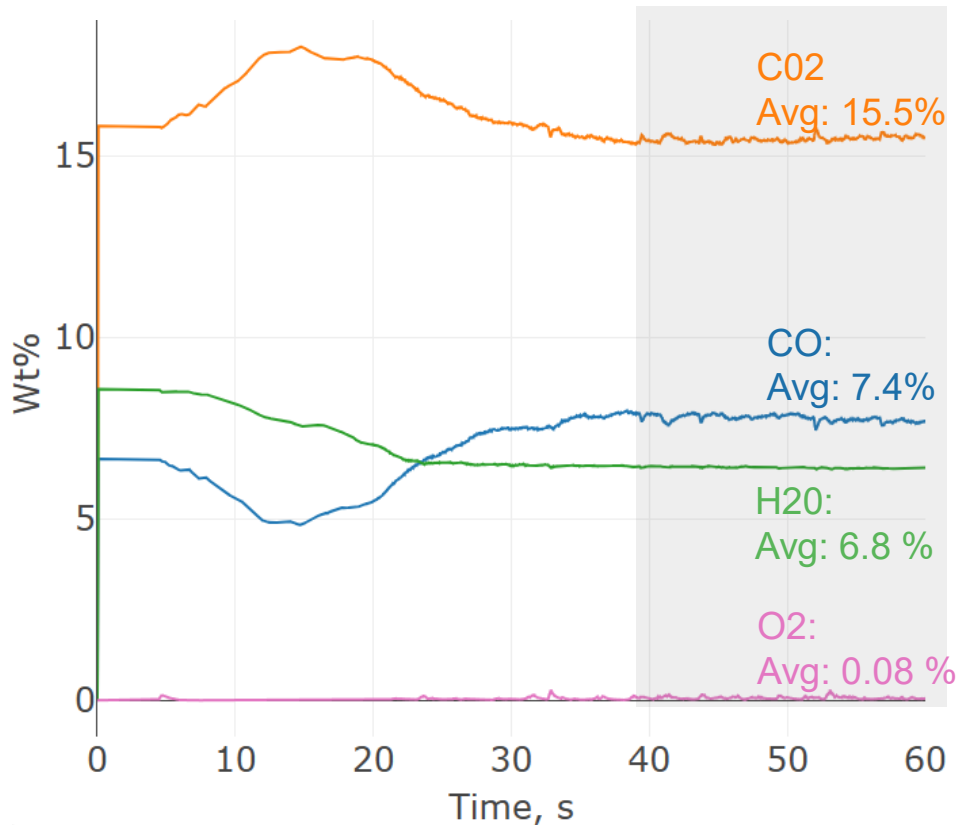
R1 Dense Phase Temp			R1 Dilute Phase Temp		
	Plant Data	CFD (last 20s avg)		Plant Data	CFD (last 20s avg)
Tap	Temp, °C	Temp, °C	Tap	Temp, °C	Temp, °C
T2A	698	700	T1A	722	718
T2B	666	697	T1B	652	698
T2C	663	666	T1C	676	675
T2D	655	675	T1D	665	674
Avg.	671	686	Avg.	679	694

# Baseline Simulations vs Plant Data: Catalyst Density Profile

- The figure shows the spatial averages of the time averaged bed density vs regenerator elevation
- 20 equally spaced points between the outer ring and the cyclone inlet were taken for calculating spatial averages. The data is hence divided into 19 bins
- For each bin, the ratio of sum of all particle volume fractions of all the cells and the total number of cells gives the average particle volume fraction for that bin
- Expected bed density from T.EN correlation and the predicted densities matched very well



# Flue gas composition and carbon burn out rate (R1)



R1 Target	Expected wt%	Predicted wt%
N <sub>2</sub>	68.63	69.8
O <sub>2</sub>	0.00	0.08
CO	6.64	7.4
CO <sub>2</sub>	15.77	15.5
SO <sub>2</sub>	0.42	0.42
H <sub>2</sub> O	8.54	6.8

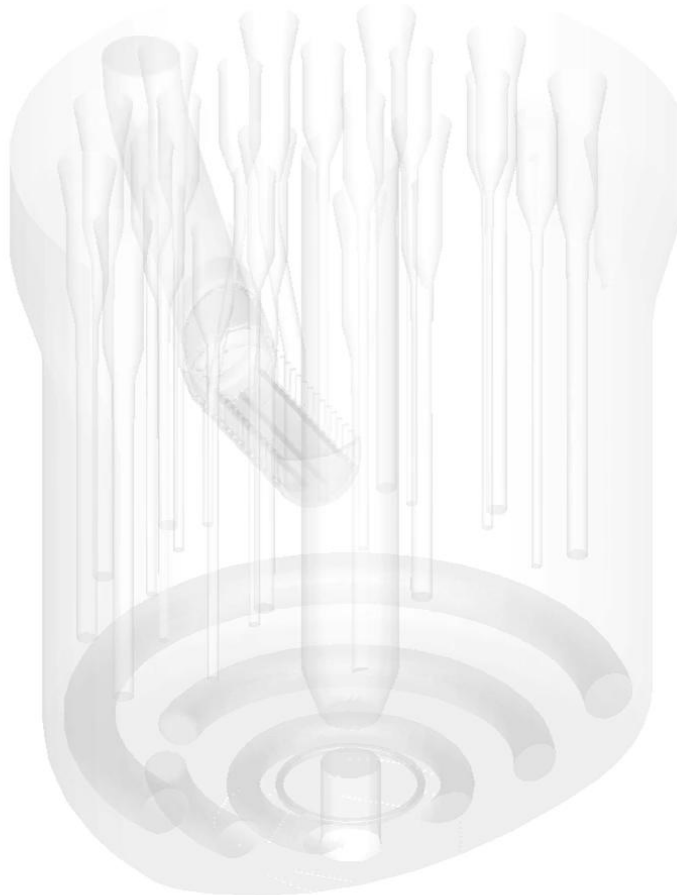
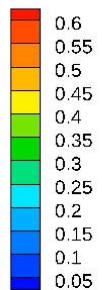
R1 Target	Expected kg/s	Predicted kg/s
Carbon Burn-Out Rate	12.3	12.6

- The predicted values were the average values between 40 and 60 s
- The CFD predicted flue gas compositions, and the carbon burn out rates were close to the expected values

# Animations: Catalyst Entry

Base case

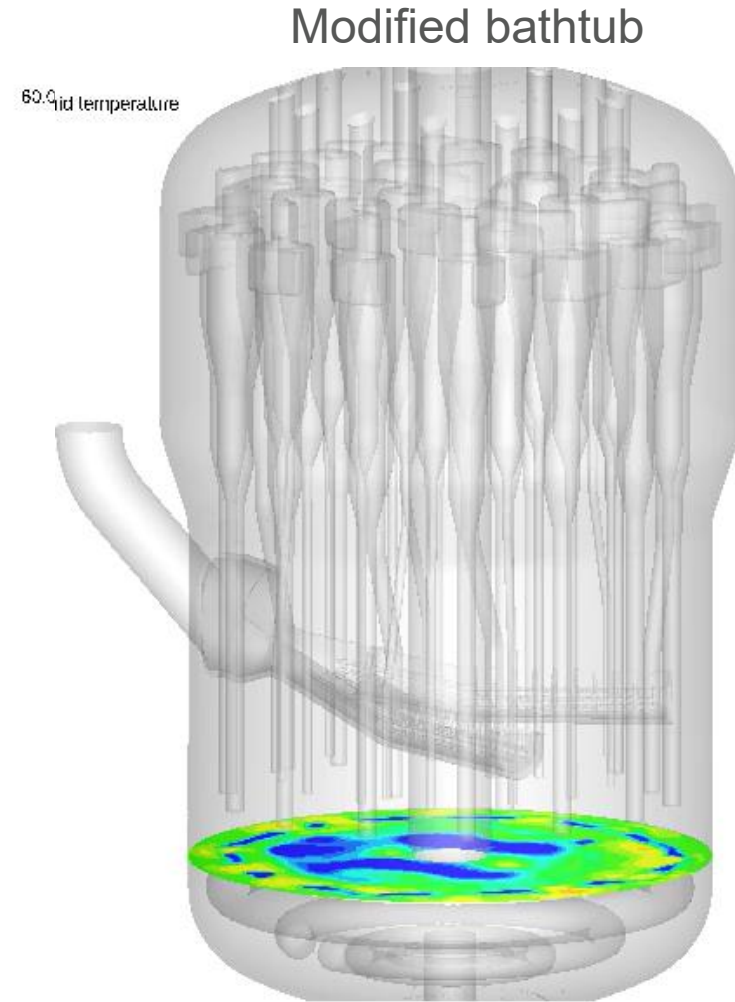
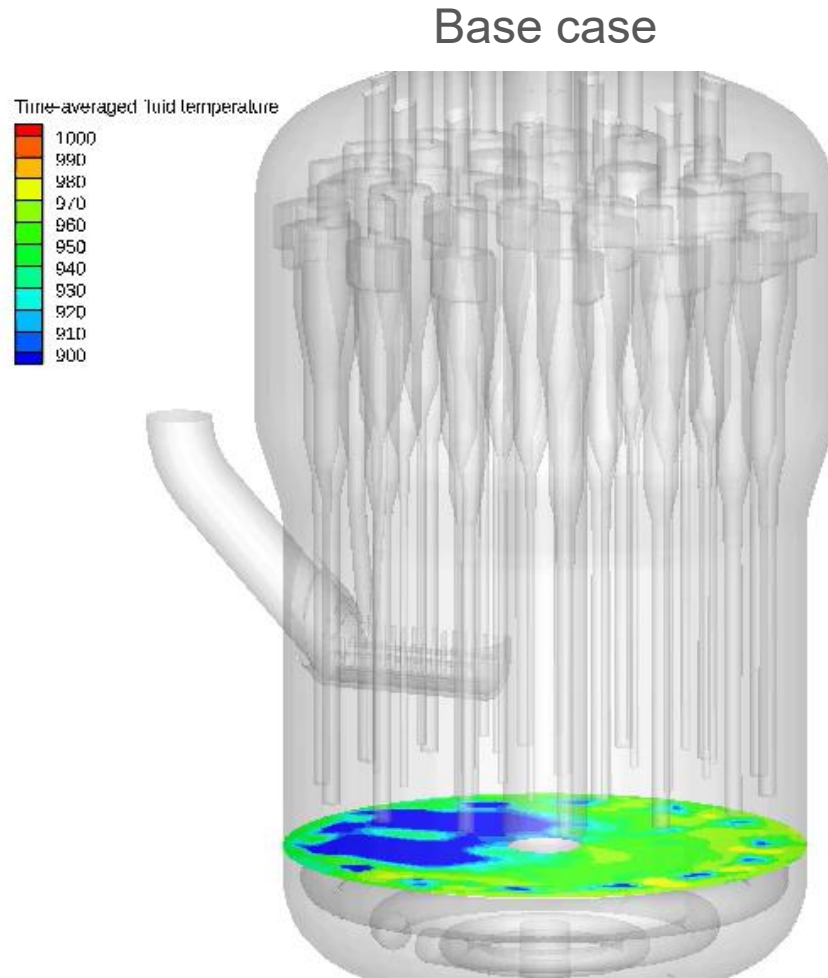
Particle volume fraction



Modified bathtub



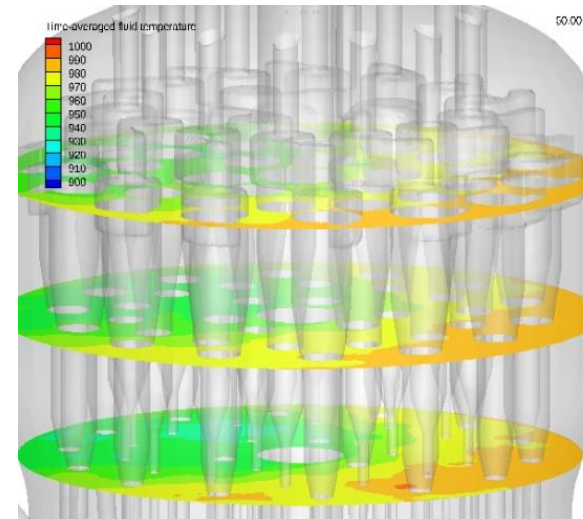
# Animations: Fluid Temperatures



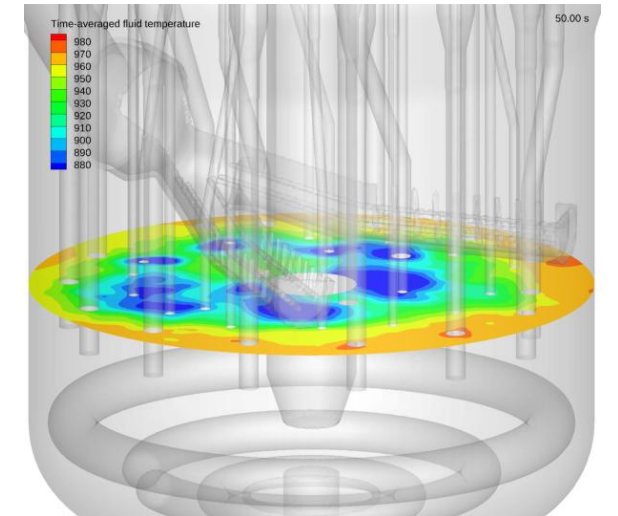
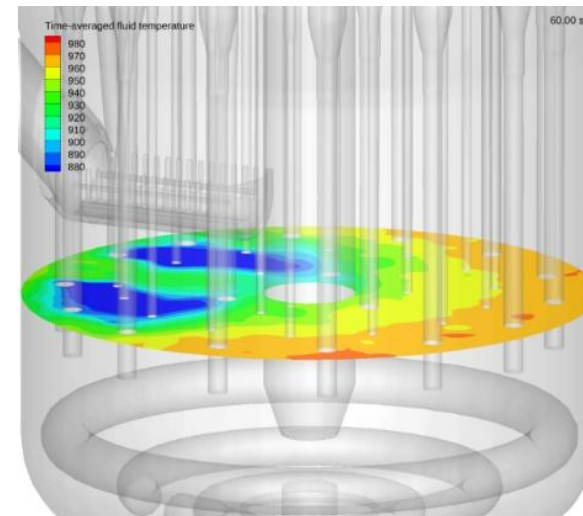
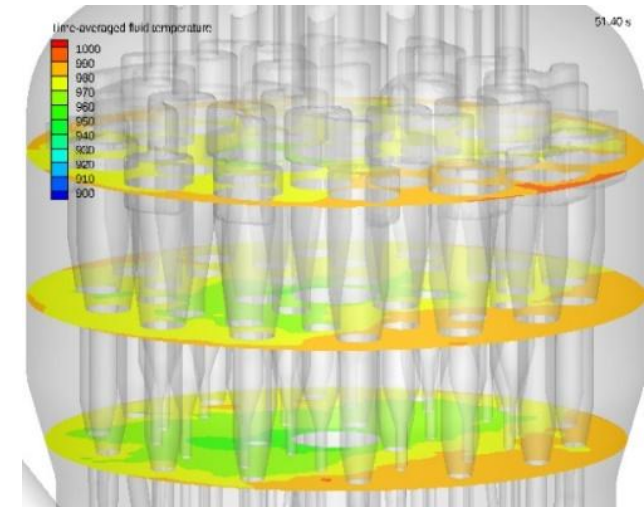
# Fluid temperatures (time averaged slices)

- Figures show slices of the time-averaged fluid temperatures in the dilute and dense phases of Regenerator 1.
- The T.EN Wye bathtub inlet design improves catalyst distribution, leading to more uniform temperature contours in the dense bed.
- Relatively low temperature spots (bottom 25% of temperature contours) are more evenly spread radially, indicating a more uniform temperature profile with the modified design.
- The inlet region shows lower temperatures compared to areas farther from the inlet, reflecting improved mixing and temperature distribution in the vessel.

Base case



Modified bathtub



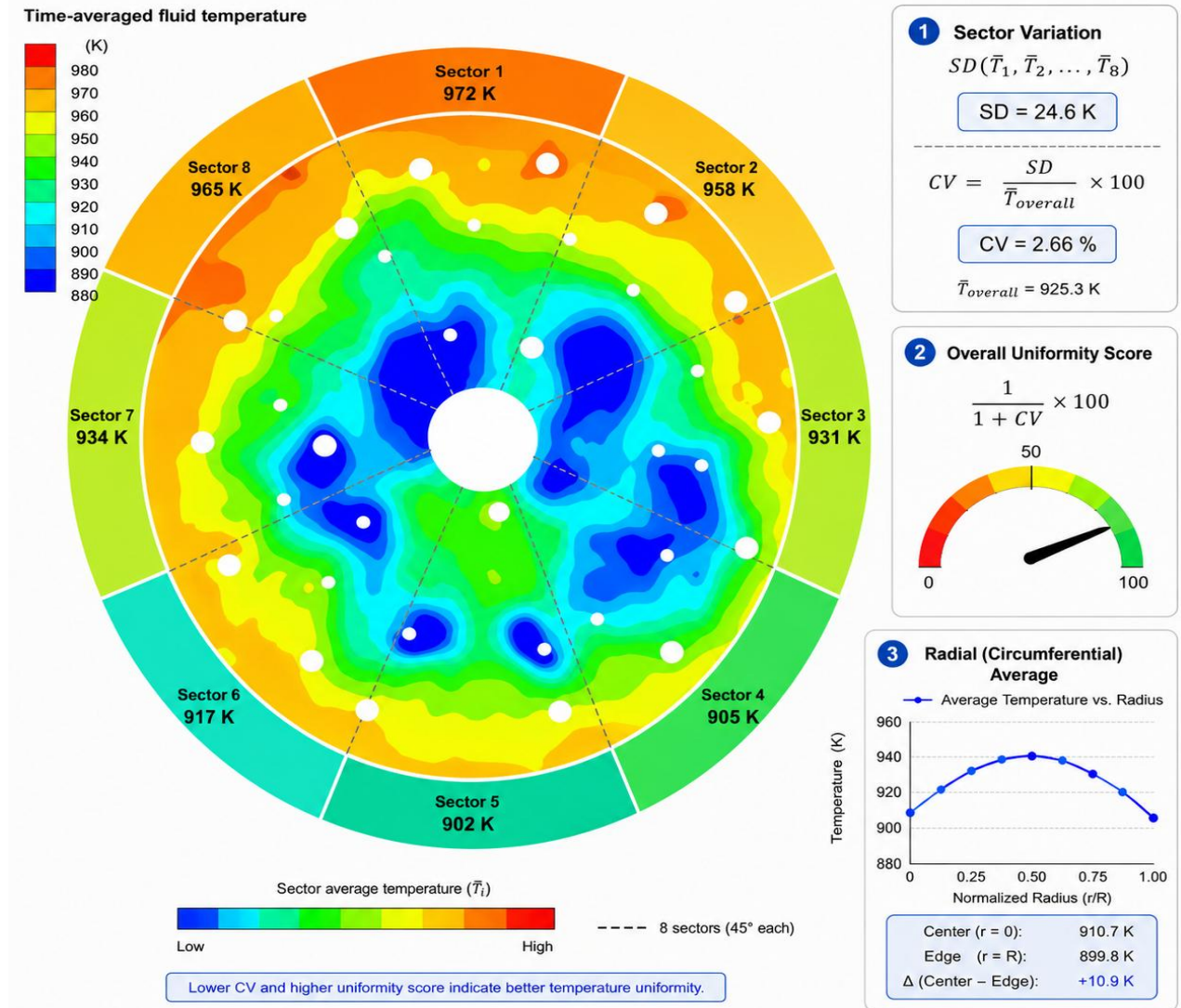
# Uniformity analysis using raw particle data

Export particle-level data to text using plt2txt or gmv2txt or connect through PyTecplot



- Sector variation  $SD(\overline{(T)}_1, \overline{(T)}_2, \dots, \overline{(T)}_8)$

- Spatial Asymmetry  $\frac{\text{Sector Variation}}{\overline{T}_{\text{overall}}} \times 100$

- Uniformity:  $\frac{1}{1 + CV}$



# Why Move from Raw Particle Data to Image-Based Analysis?

Aspect	Raw particle Data	Image Based
Purpose	Validation benchmark	Fast screening
Input	Particle data	Contour images
Speed	Minutes to hours 	Hundreds of slices in seconds 

**1. Raw Particle Benchmark**

- Extracted particle data
- Checked clipping effects
- Calculated benchmark metrics



**2. Image Model Calibration**

- Generated validated contours
- Masked non-fluid regions
- Calibrated RGB values
- Matched particle benchmark



**3. Fast Screening Workflow**

- Avoids repeated raw extraction
- Computes metrics from images
- Screens many cases quickly

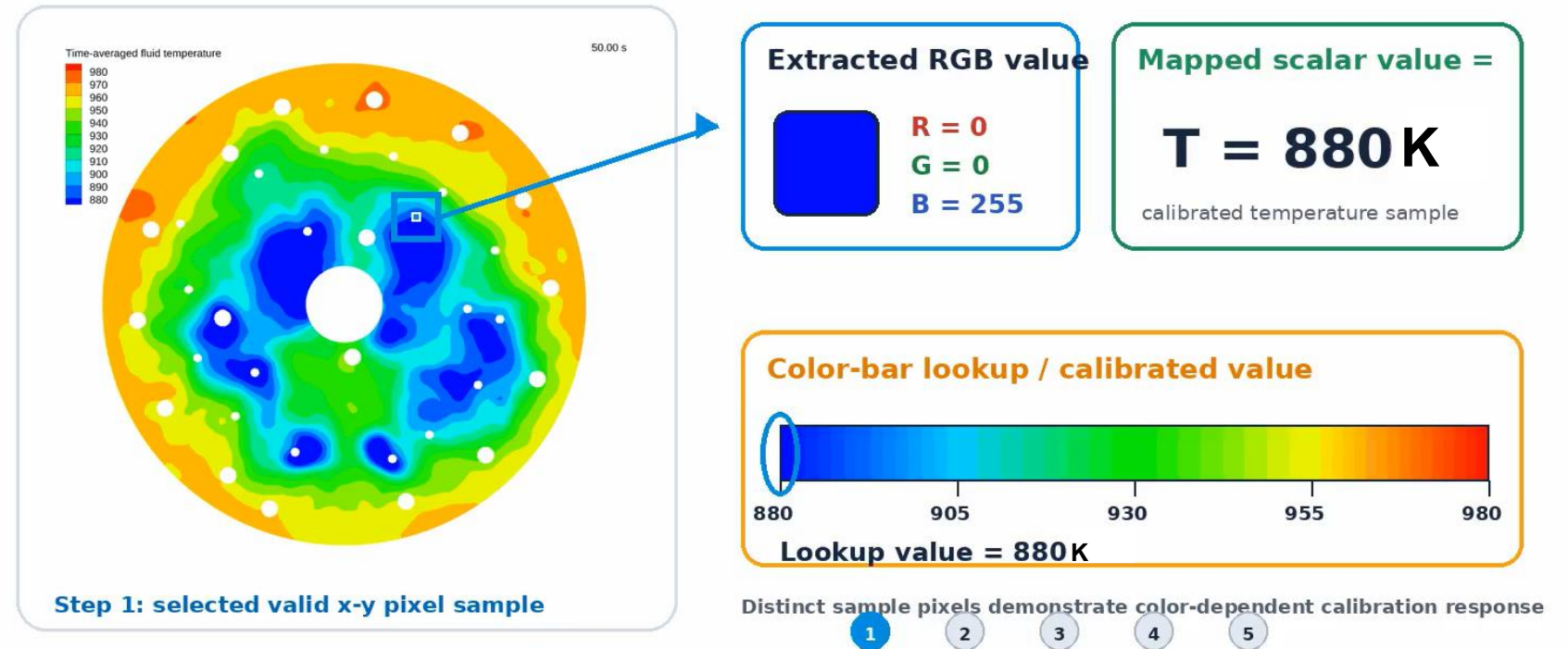
**<1%**  
Target error vs. particle benchmark

# Converting Image Color into Temperature Data: Pixel Calibration:

- A selected valid pixel is highlighted on the temperature contour
- The pixel color is extracted as RGB values
- RGB values are matched to the calibrated color bar
- The lookup result is converted into a scalar temperature value

## Pixel calibration: one pixel → complete calibrated data record

For each highlighted pixel, RGB extraction, colorbar lookup, and mapped scalar temperature are generated together.



Pixel(x, y) → RGB(R, G, B)

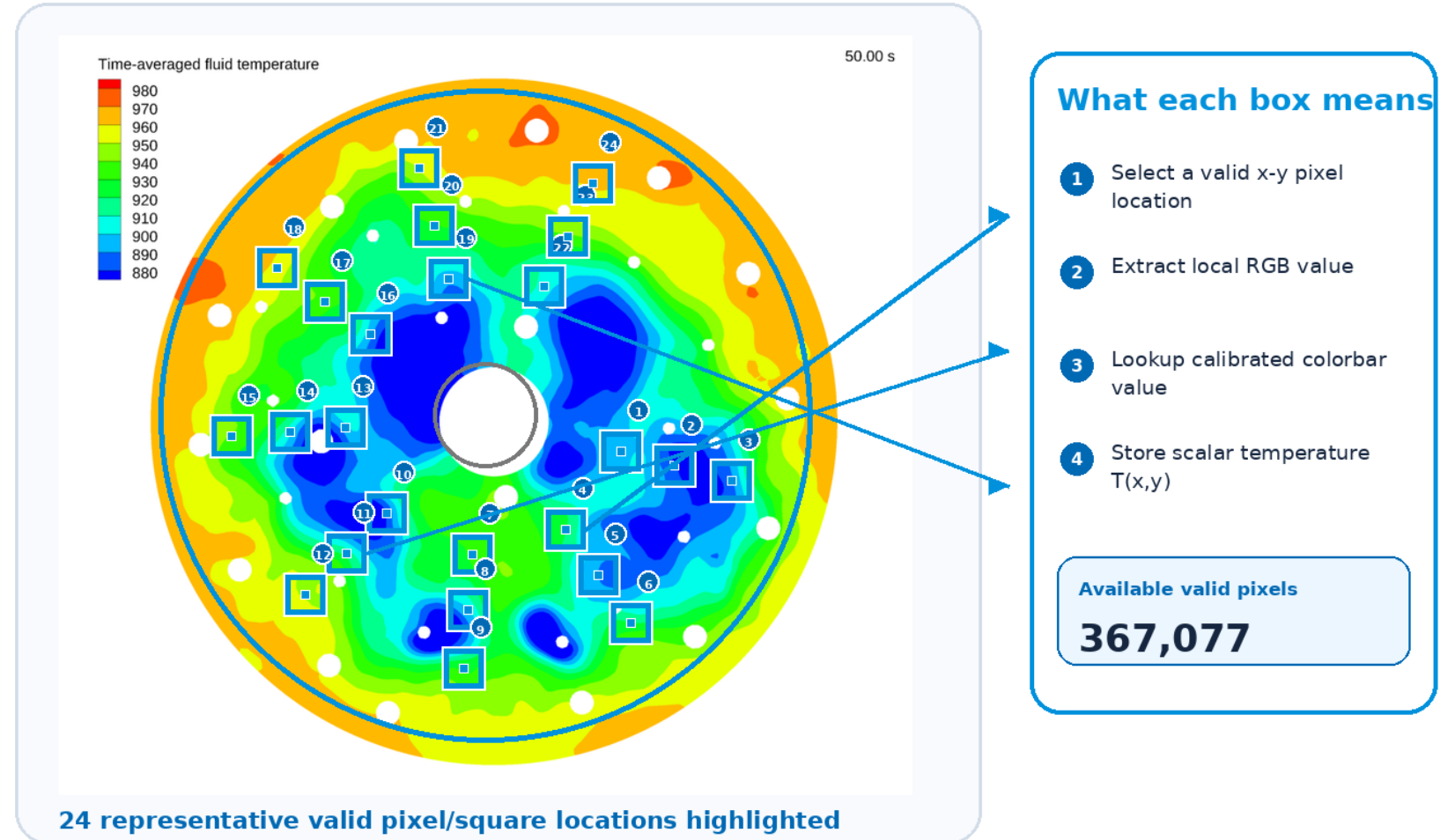
Total = 367,000 valid pixels

# Representative Pixel Sampling for Image-Based Calibration

- Cyan squares show selected valid pixel locations
- Each sample is converted from RGB to temperature
- The workflow is repeated across all valid pixels
- Visible samples represent the full pixel-based analysis

## Multiple Valid Pixel Samples Highlighted for Calibration

Each cyan square marks a selected valid pixel/small square region; all highlighted samples would be converted using the same RGB → color



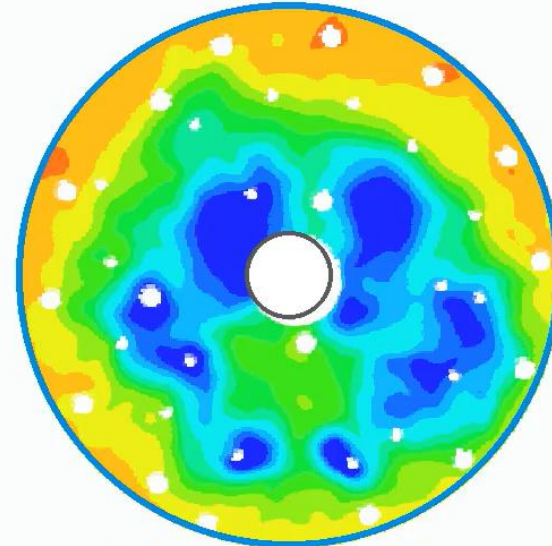
Note: cyan boxes are enlarged visual callouts; each box represents a selected valid pixel/small square region from the underlying temperature contour.

# Sector-Based Uniformity Metric Calculation

- The reconstructed temperature field is divided into eight angular sectors
- Each sector collects valid calibrated pixels within its angular range
- Mean temperature is calculated independently for each sector
- Sector means are compared to quantify angular variation and spatial asymmetry

## Sector metric calculation from reconstructed field

The reconstructed temperature field is divided into eight angular sectors and converted into uniformity metrics.



reconstructed x-y temperature field

### Input: reconstructed field

- Each valid pixel now contains a calibrated temperature value  $T(x,y)$ .
- The next step is to summarize the field by angular location.

### Pixel record

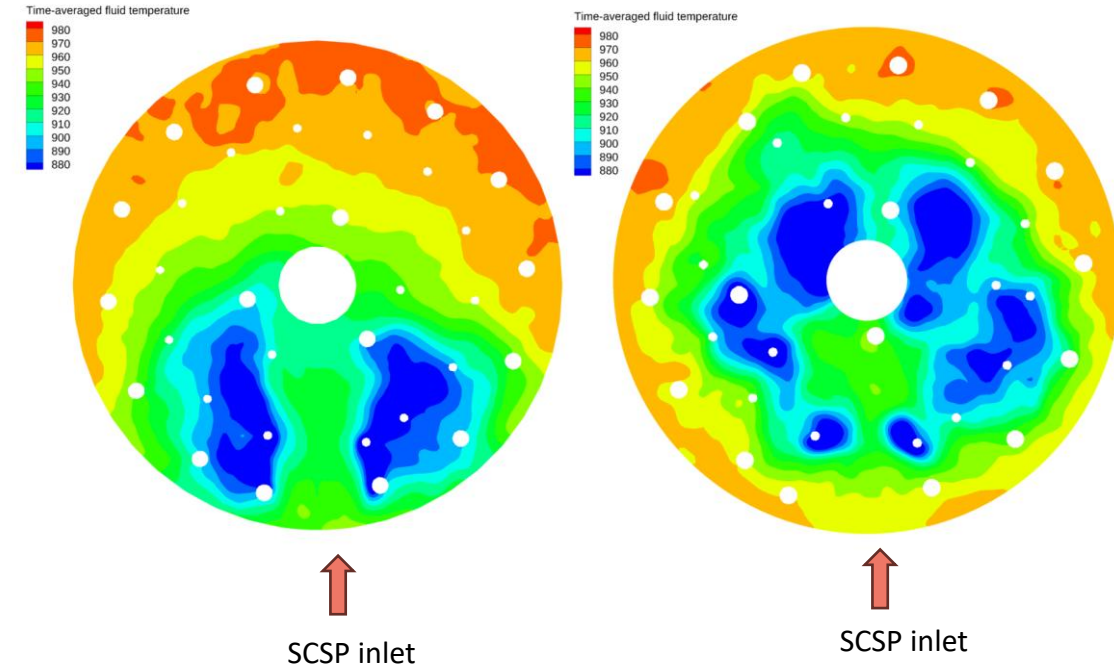
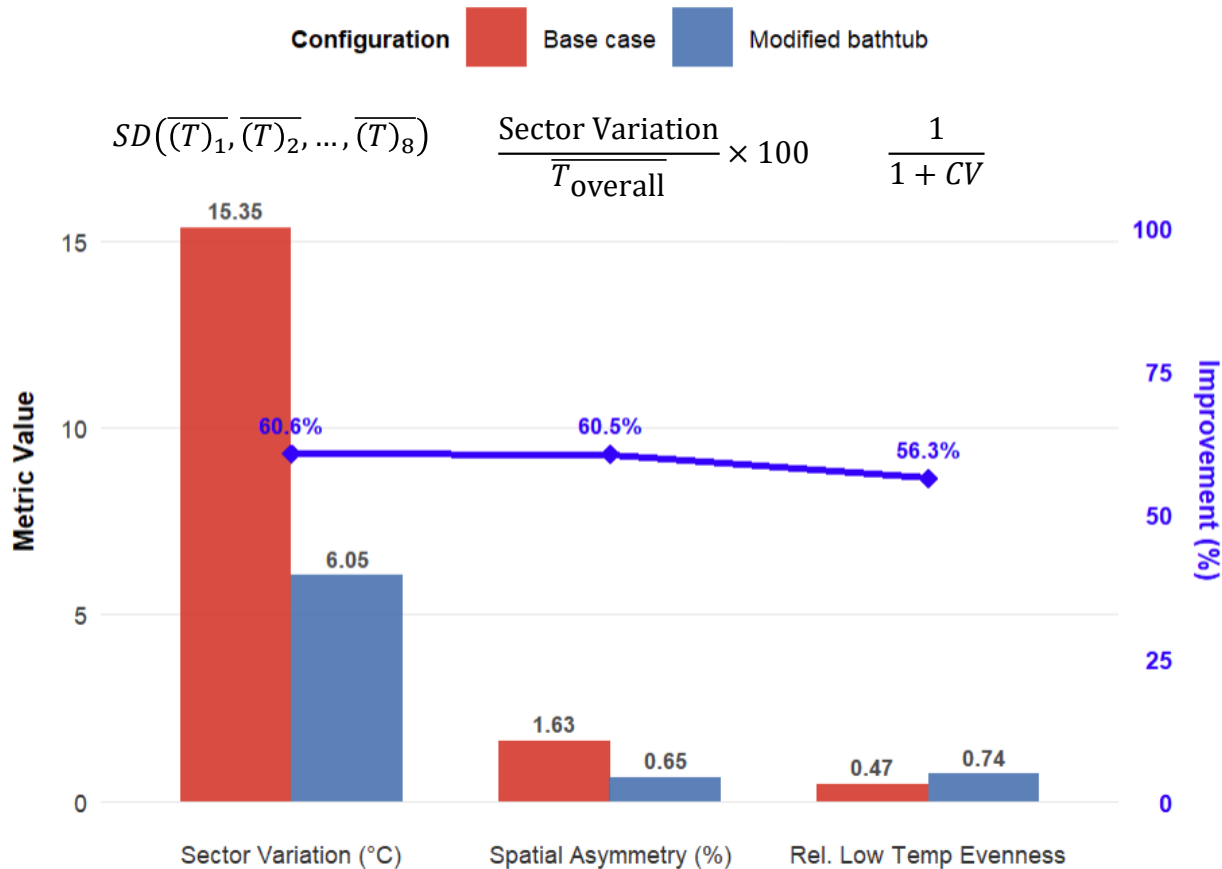
(x, y, T)



# Quantitative Metrics Comparison : Temperature Uniformity

## Uniformity Metrics: Absolute Values & Percentage Improvement

Bars show absolute metric values | Green line shows % improvement (Modified vs Base)

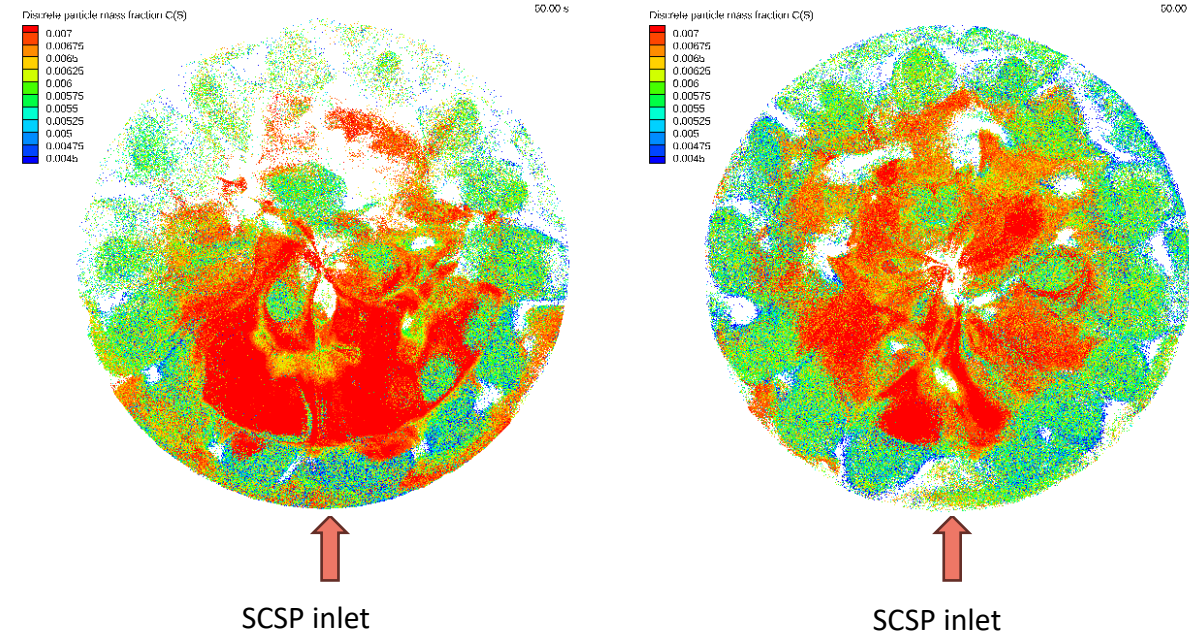
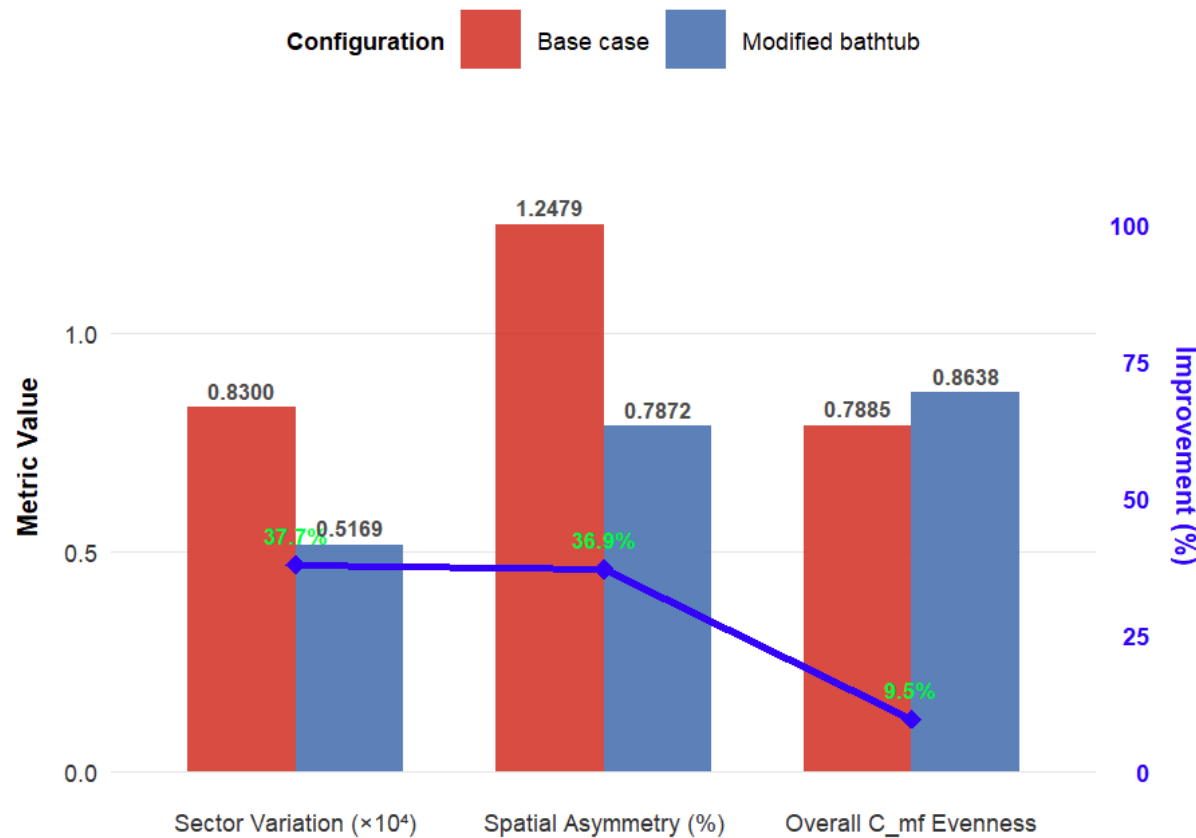


- Modified bathtub improves temperature uniformity across all metrics
- Sector variation & spatial asymmetry ↓ 61%; relatively low temperature evenness ↑ 57%
- Result: more uniform temperature and catalyst distribution with fewer hot/cold spots

# Quantitative Metrics Comparison: Catalyst distribution from SCSP

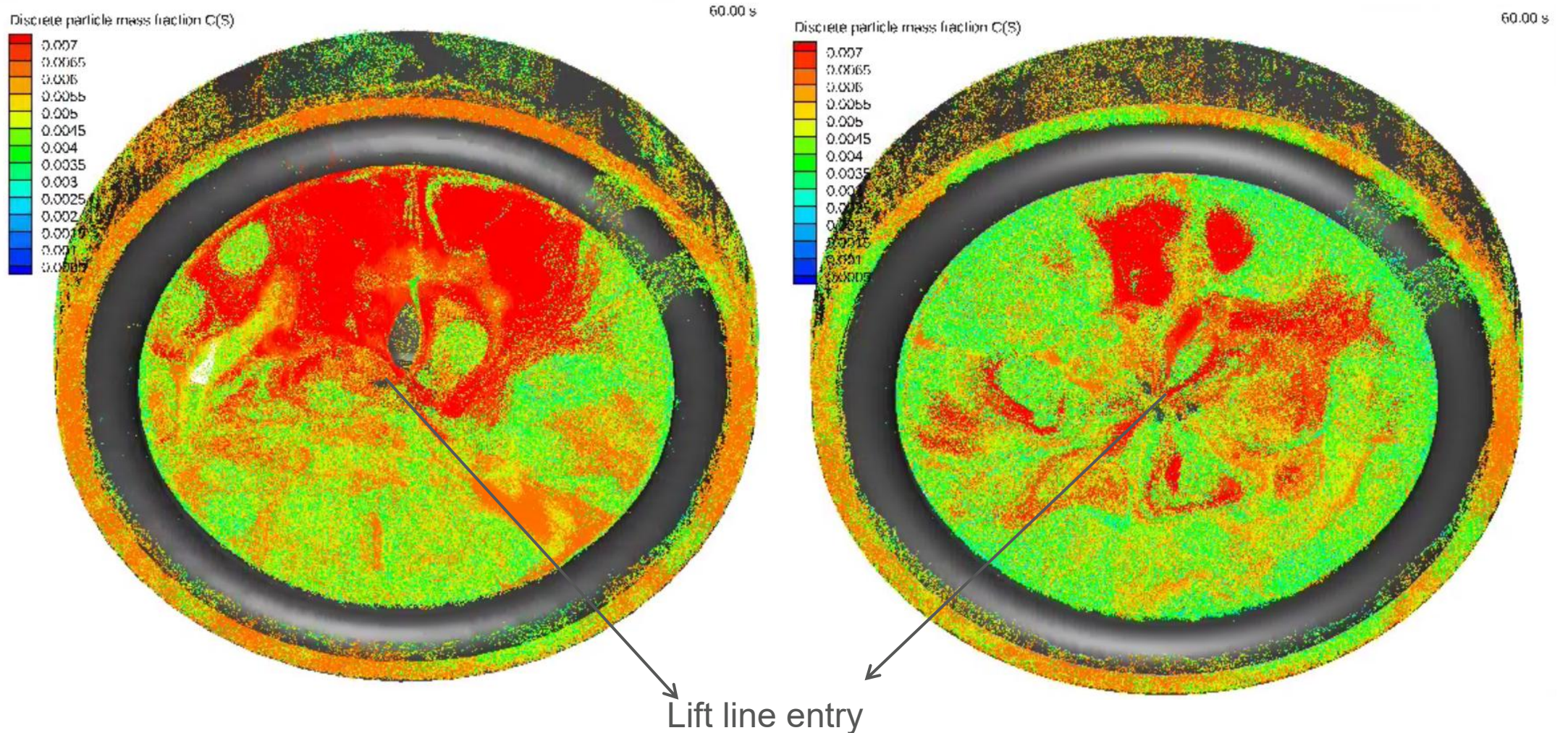
## Carbon Mass Fraction Uniformity: Absolute Values & Improvement

Bars show absolute metric values | Green line shows % improvement (Modified vs Base)



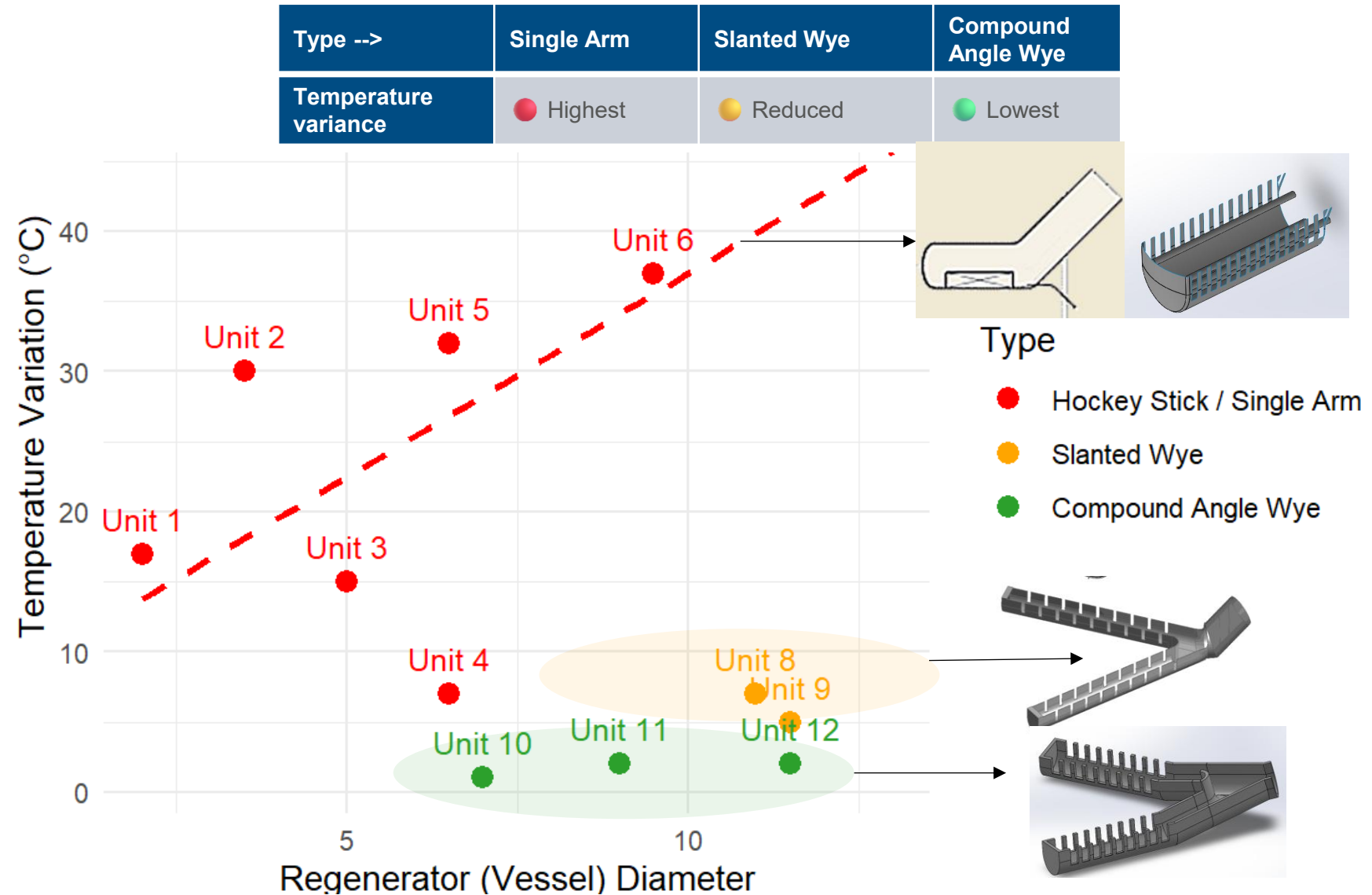
- Modified bathtub shows improved carbon mass fraction uniformity across all metrics
- Sector variation  $\downarrow$  ~38% and spatial asymmetry  $\downarrow$  ~37%, indicating more even distribution
- Evenness  $\uparrow$  ~15%  $\rightarrow$  reduced clustering and more uniform solids distribution across the vessel

# Distribution of incoming Carbon from SCSP



# Survey of Commercial units

- Moving to a compound-angle Wye reduces dense bed temperature variation
- This improves distribution and helps in minimizing coke load and reducing afterburn in R2

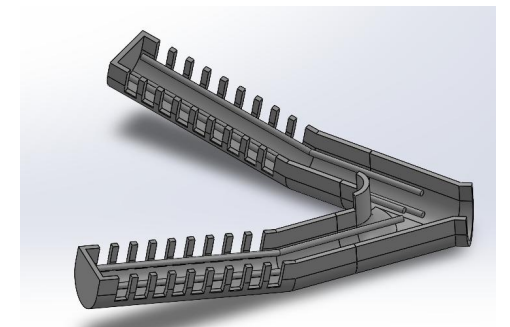
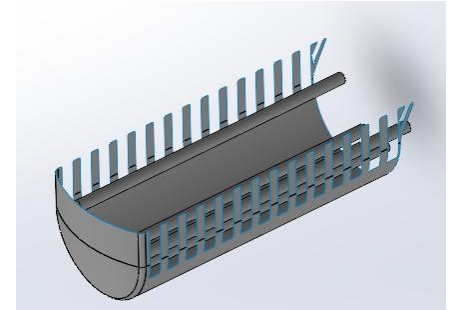


# Conclusion

- An in-depth hydrodynamic and kinetic CFD study confirms that the proposed design modifications significantly enhance regenerator performance.
- Regenerator 1: Key Findings
  - ~60% improvement in temperature uniformity (dense bed)
  - ~37% improvement in spent catalyst carbon distribution uniformity
  - Reduced spatial asymmetry and sectoral variation

## Impact:

- Improved catalyst distribution ensures a stable and uniform temperature profile, aiding better operation
- Uniform solids distribution in R1 minimizes the risk of afterburn in R2 since unburnt coke carryover increases regenerator load and demands more complete combustion.





# Thank you