Recent Cinar Work on, AFR, NOx and CO:

30-31st of May 2012

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AFR Programme – WP

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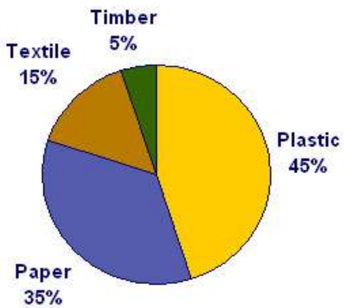
AFR Opportunities



Biosolids

Av. Size: 50 μm

Solid Recovered Fuel

Av. Size: 2 mm

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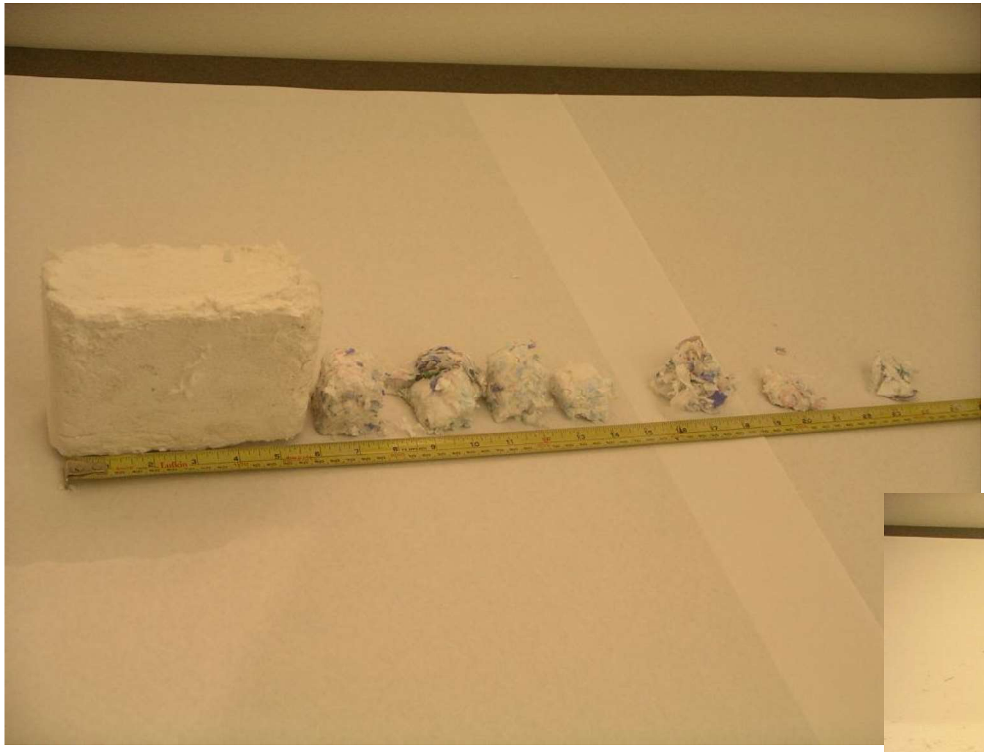
Diaper Cubes & Tire Chips



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AFR in Calciners!

Higher AFR Substitution (up to 90%) Several injection locations;

Bigger Size (50-60 mm) AFR as compared with Kiln burner (3-5 mm);

Potential of reducing kiln generated CO and NOx (up to 80%);

Potential of reducing kiln instability (less build-up and SO3);

Difficult to design a generic burner (mono-channel/multi-channel?)

One Needs a different Approach!

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Calciner AFR Constrains!

One needs precise flow and undergoing reaction information inside a calciner:

(1) Both Fuel and meal's best injection locations;

(Michalis/Joana/Tom)

(2) The Design of a Venturi (for bigger AFR fraction)!

(Michalis)

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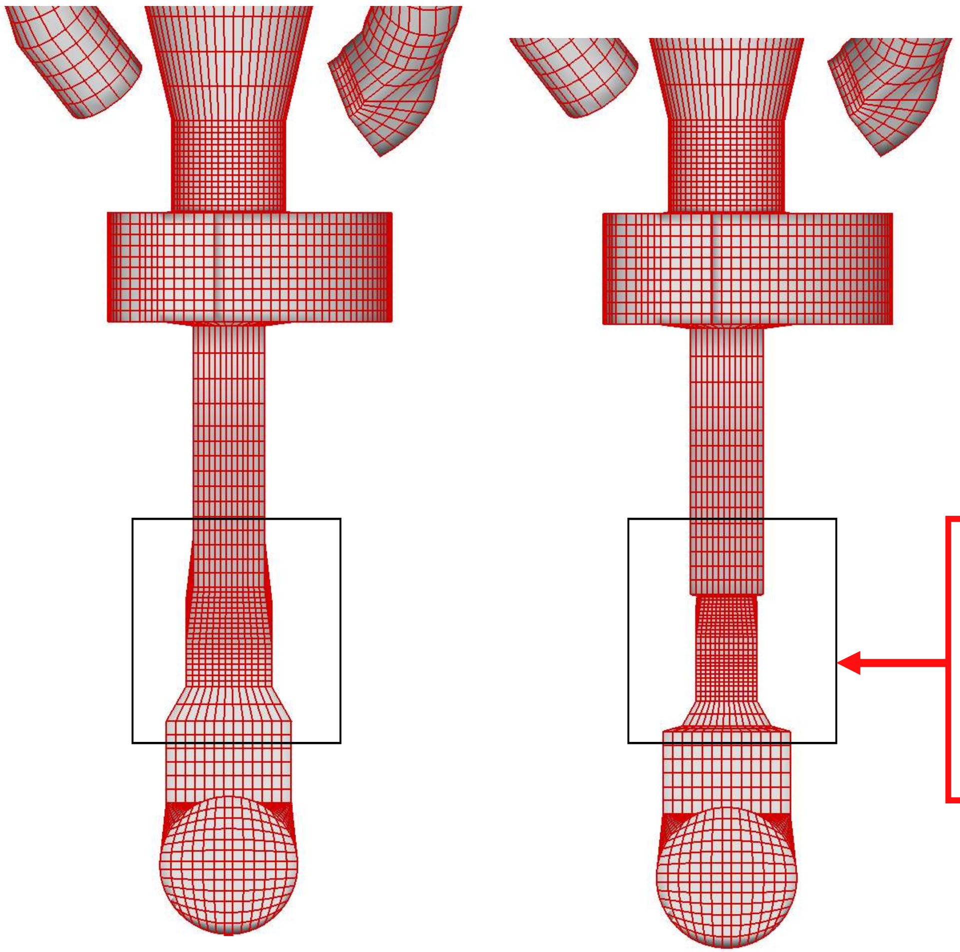
Geometry and Dimensions

Without Venturi   With Venturi



3-4 meters in length, upward flow velocity to 40-45 m/s for 50x50x10 mm chipped tyres

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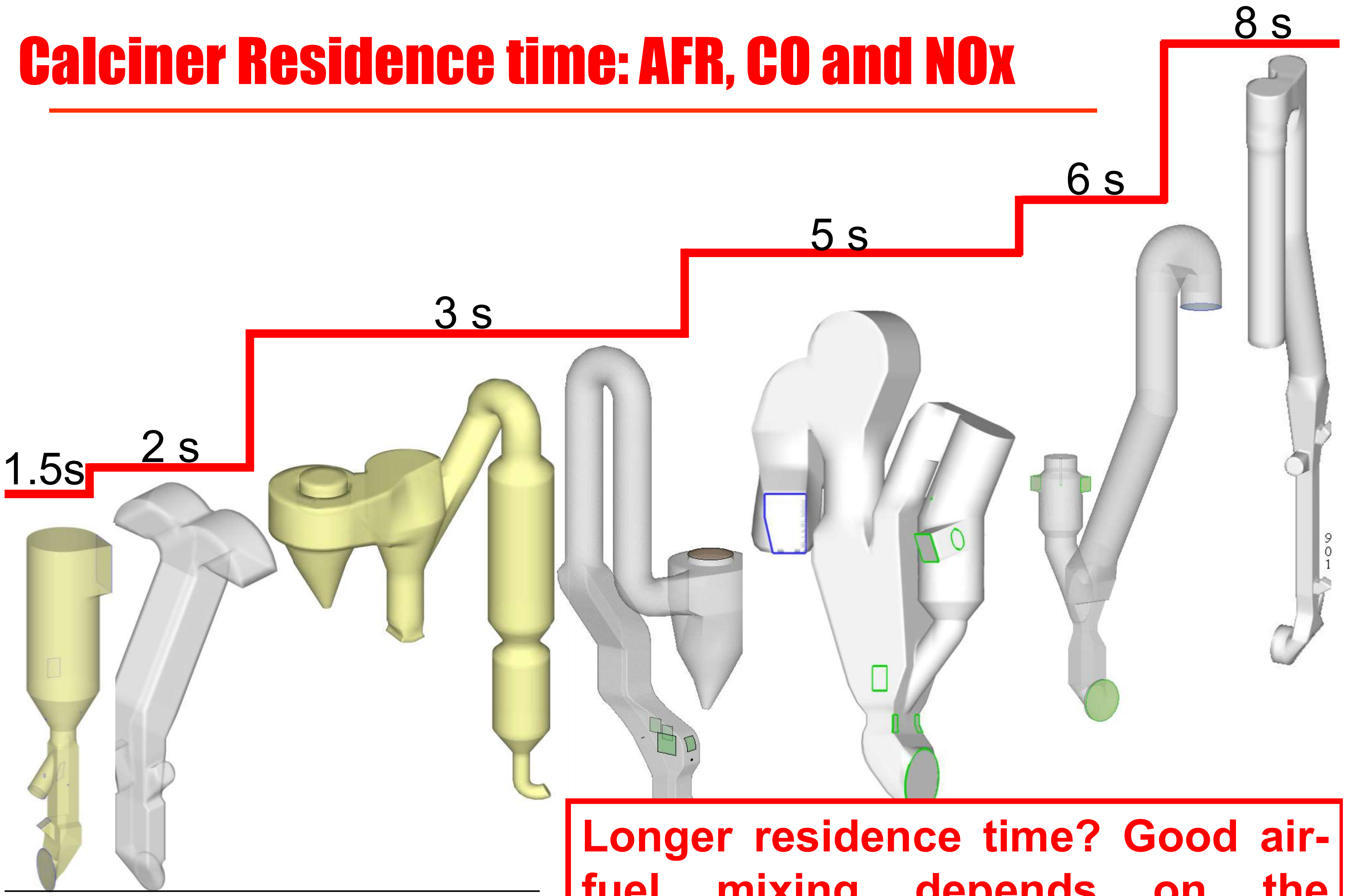
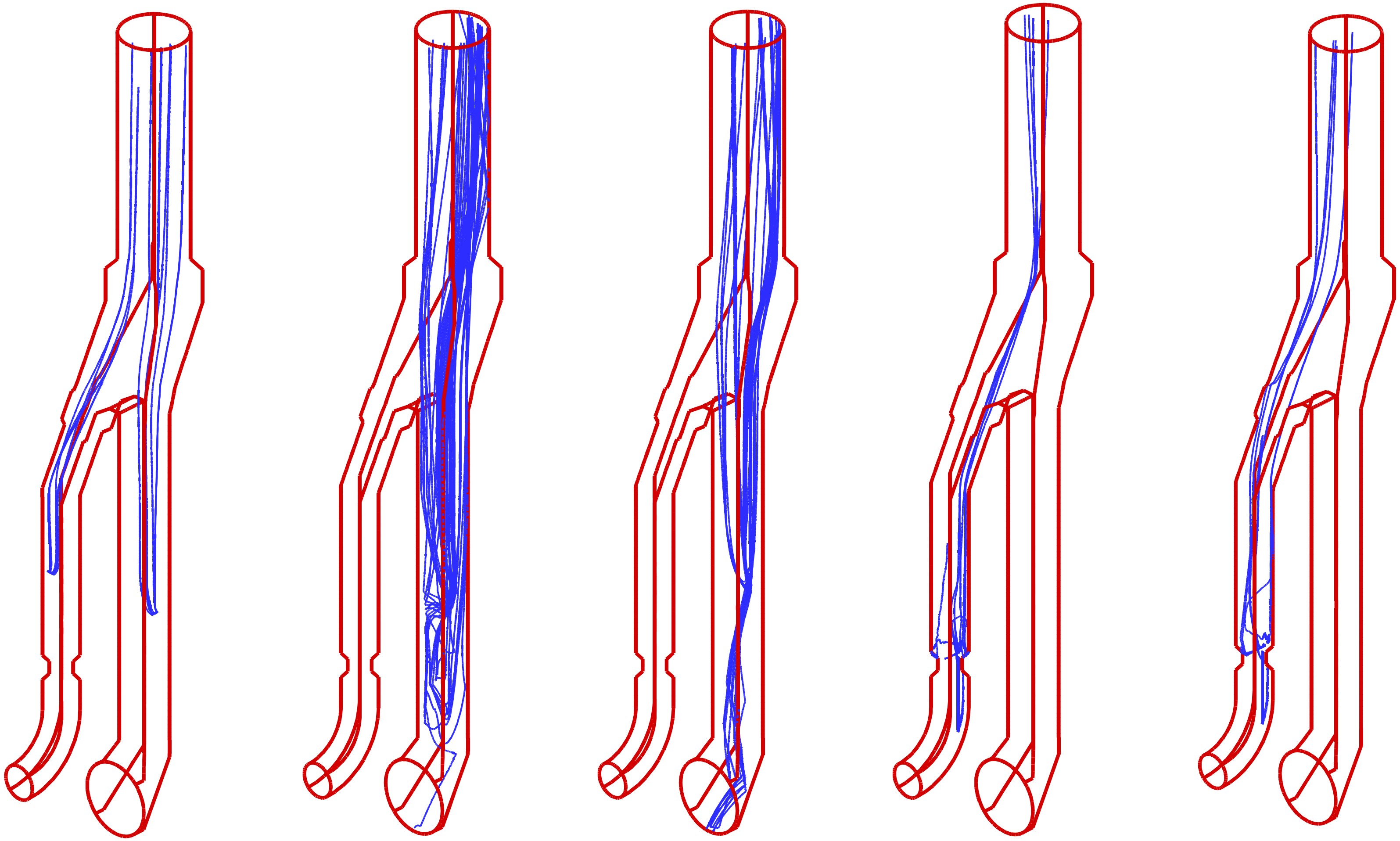
Calciner Residence time: AFR, CO and NOx



Longer residence time? Good air-fuel mixing depends on the objectives (AFR or CO or NOx!

Solid-Fuel Trajectories



Coal **Tire Chips** **Diaper** **Plastic Disk** **Wood Chips**

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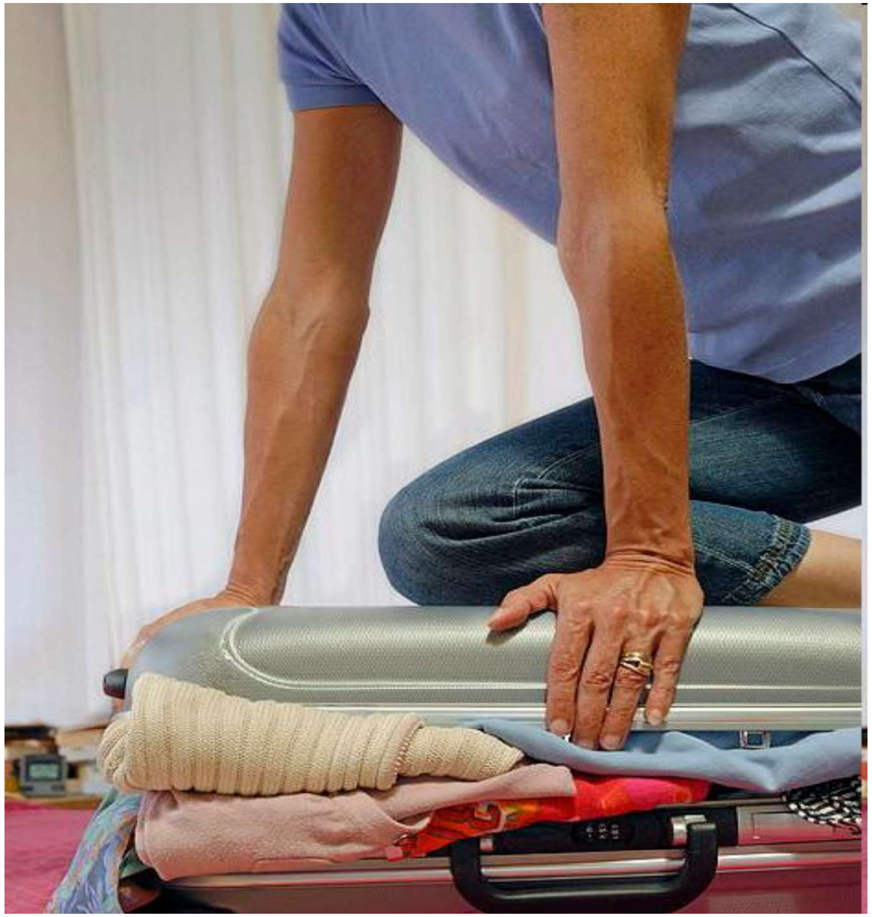
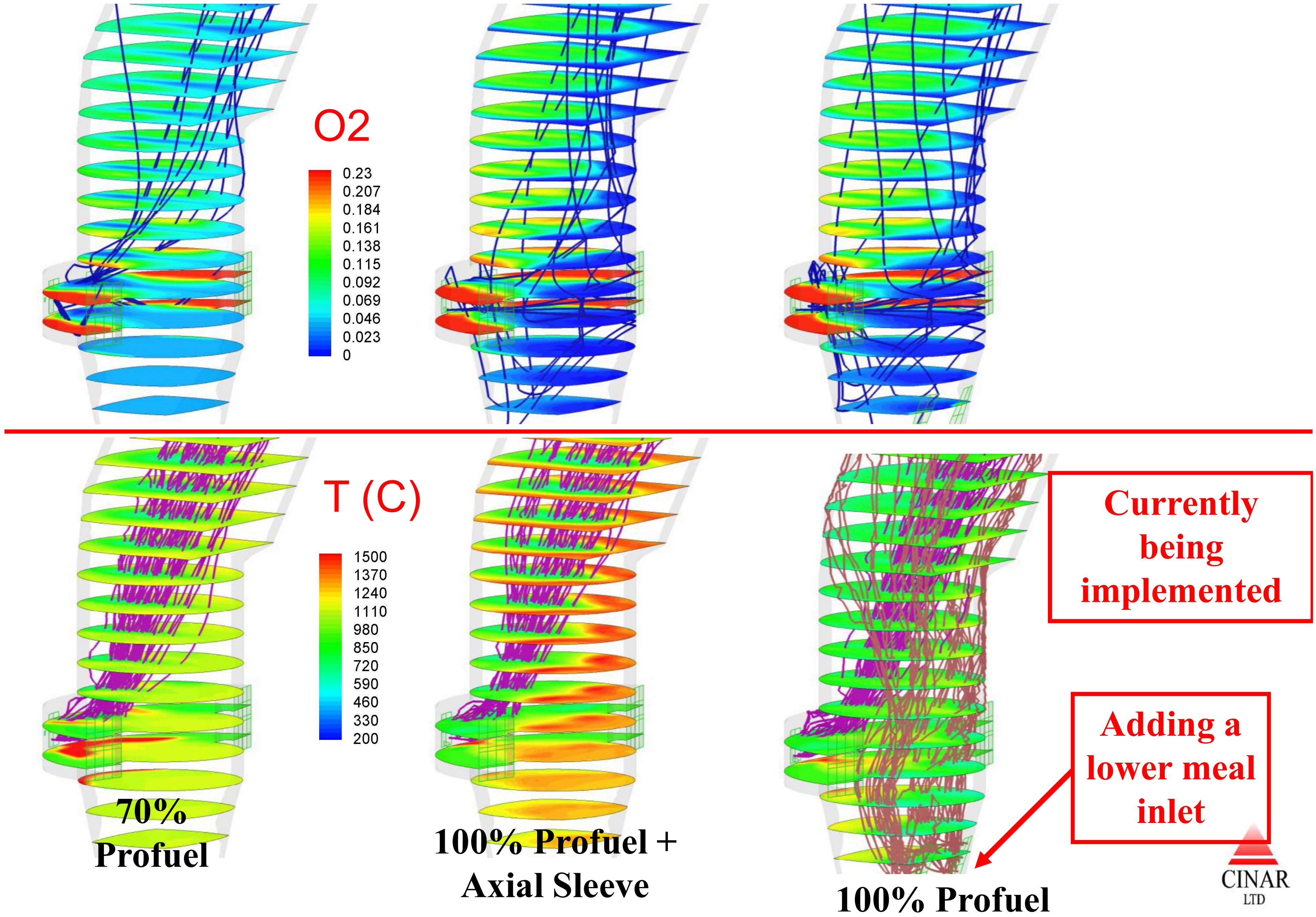
House in Order?



Profuel particles in O2-Meal particles in Temperature



Created Hot-Wall instead of Hot-spot !

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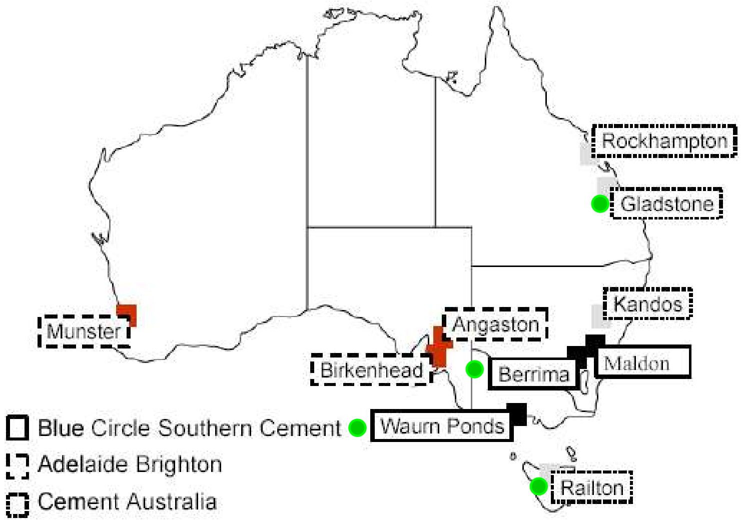
Case Study: Boral Cement Waurn Ponds Australia

Alternative Fuel and Raw Material Programme



Cement Plant Locations in Australia

Boral Cement at Waurn Ponds:
75% Biosolids via the burner and 90% SRF into a KHD Calciner

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CO and NOx reduction in Calciners:

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CO Formation

- Most of CO is released during the final stages of primary devolatilisation, or the secondary pyrolysis;

- CO continues to be generated from heterogeneous char oxidation which is even more complex.

$$\boxed{2C + O2 \longrightarrow C(O) + CO}$$

$$\boxed{C(O) \longrightarrow CO}$$

where C(O) is the oxide complex on the carbon surface

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CO Reduction

■ $CO + OH$	$\longrightarrow$ $CO_2 + H$	(1)	
■ $O_2 + H + M$	$\longrightarrow$ $HO_2 + M$	(2)	Reactions 1-4 are the most important for the CO consumption as well as to OH yield,
■ $O_2 + H$	$\longrightarrow$ $OH + O$	(3)	
■ $HO_2 + OH$	$\longrightarrow$ $O_2 + H_2O$	(4)	
■ $HO_2 + HO_2$	$\longrightarrow$ $H_2O_2 + O_2$	(5)	
■ $H_2O + O$	$\longrightarrow$ $OH + OH$	(6)	Reactions 5-7 are of moderate to weak importance; Thornton et al. (Combust. Sci, and Tech., 1987),
■ $CO + O + M$	$\longrightarrow$ $CO_2 + M$	(7)	

$$\boxed{CO + OH \longrightarrow CO_2 + H}$$

The most effective CO reduction reaction

$$\boxed{CO + O_2 \longrightarrow CO_2 + O}$$

The least important reaction

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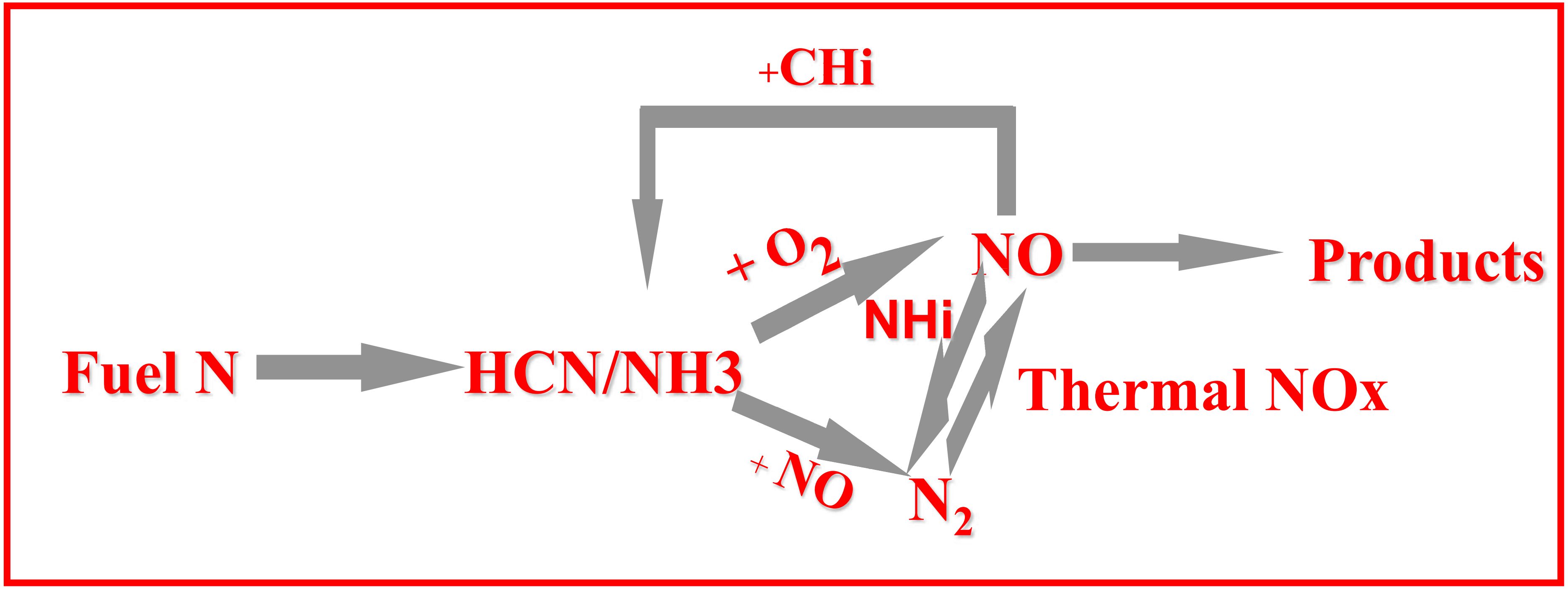
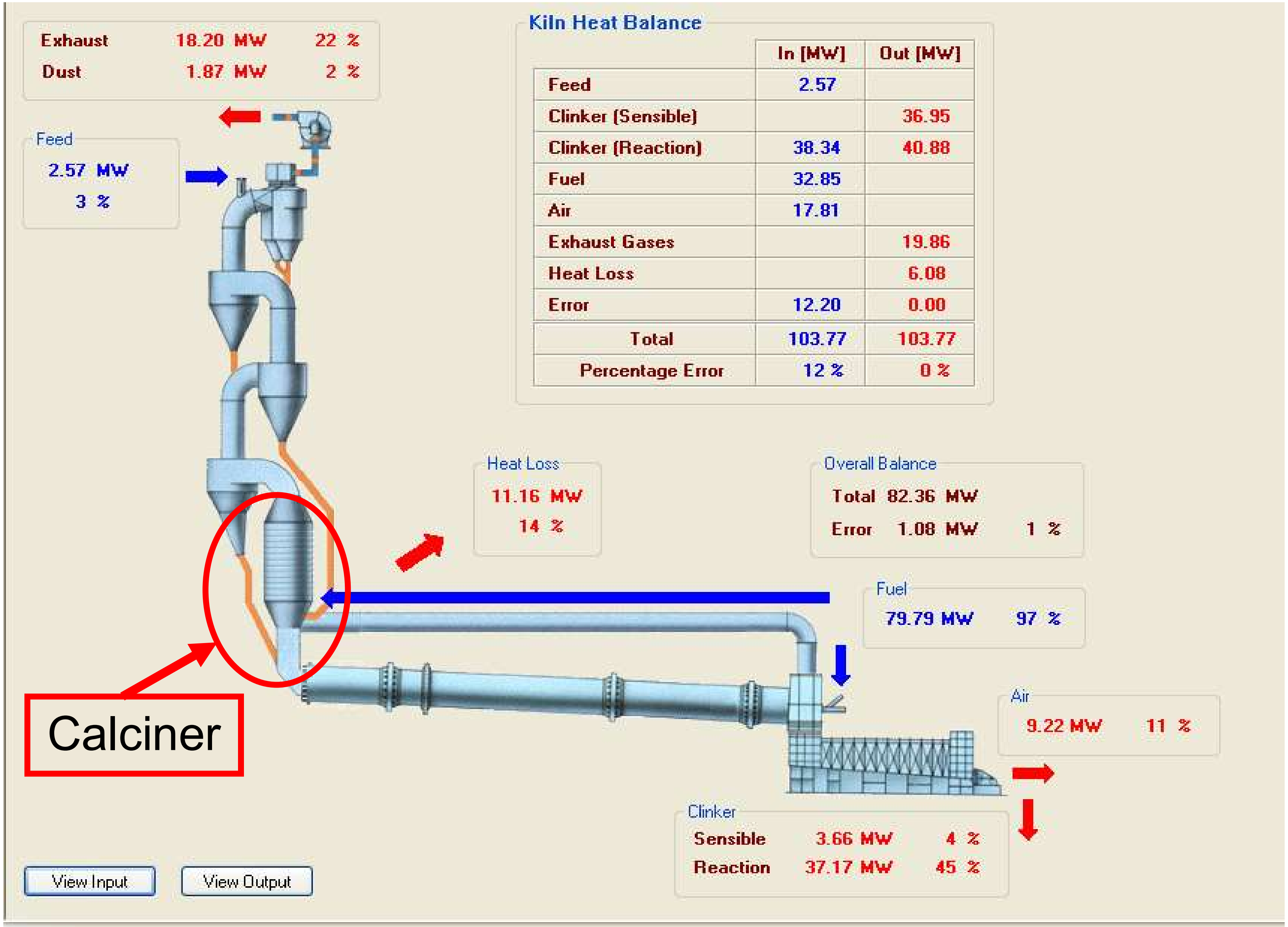
Post-Processing for Trace Species

- Proven global reactions are used for the nitrogenous species.



Calciner (Less Visible but ….)



	In [MW]	Out [MW]
Feed	2.57	
Clinker (Sensible)		36.95
Clinker (Reaction)	38.34	40.88
Fuel	32.85	
Air	17.81	
Exhaust Gases		19.86
Heat Loss		6.08
Error	12.20	0.00
Total	103.77	103.77
Percentage Error	12 %	0 %

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Reducing Kiln NOx

Producing a ‘lit-back’ flame with minimum air premixing of the kiln burner;

Creation of a ‘short-sharp kiln flame-reducing the higher-temperature flame envelop for lower thermal NOx formation;

Mid-kiln, kiln back-end fuel (AF) injection (CO emissions, JAMS)

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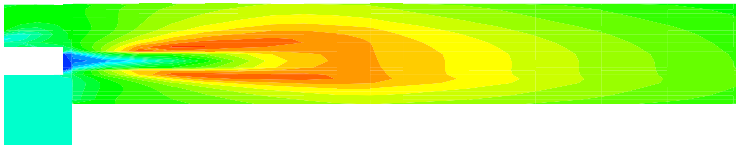
Reducing Kiln NOx

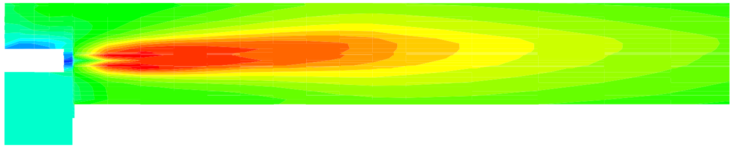
Mono-channel burner

Estimated Flame Length:	20-25 m
Ignition distance:	1.5-2 m
Exit NOx:	1049 ppm



Multi-channel burner

Reduction in Flame Length:	5 m
Reduction in Ign. distance:	1 m
Exit NOx:	634 ppm



Plant Feed Back:

- NOx emissions 620 ppm

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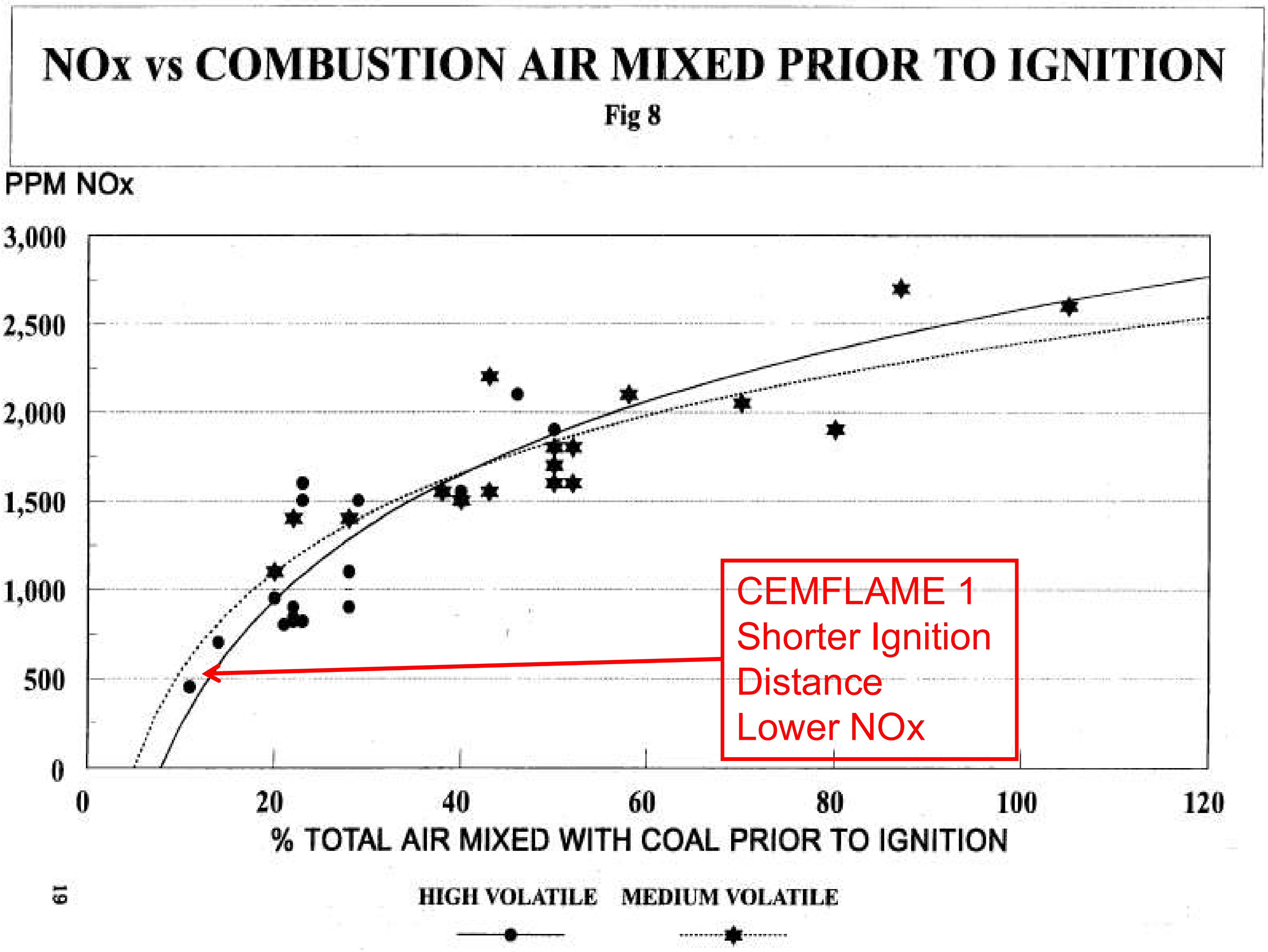

NOx vs COMBUSTION AIR MIXED PRIOR TO IGNITION
Fig 8
PPM NOx
3,000
2,500
2,000
1,500
1,000
500
0
0
20
40
60
80
100
120
% TOTAL AIR MIXED WITH COAL PRIOR TO IGNITION
HIGH VOLATILE
MEDIUM VOLATILE
CEMFLAME 1
Shorter Ignition
Distance
Lower NOx
19

Reducing Kiln CO Emissions

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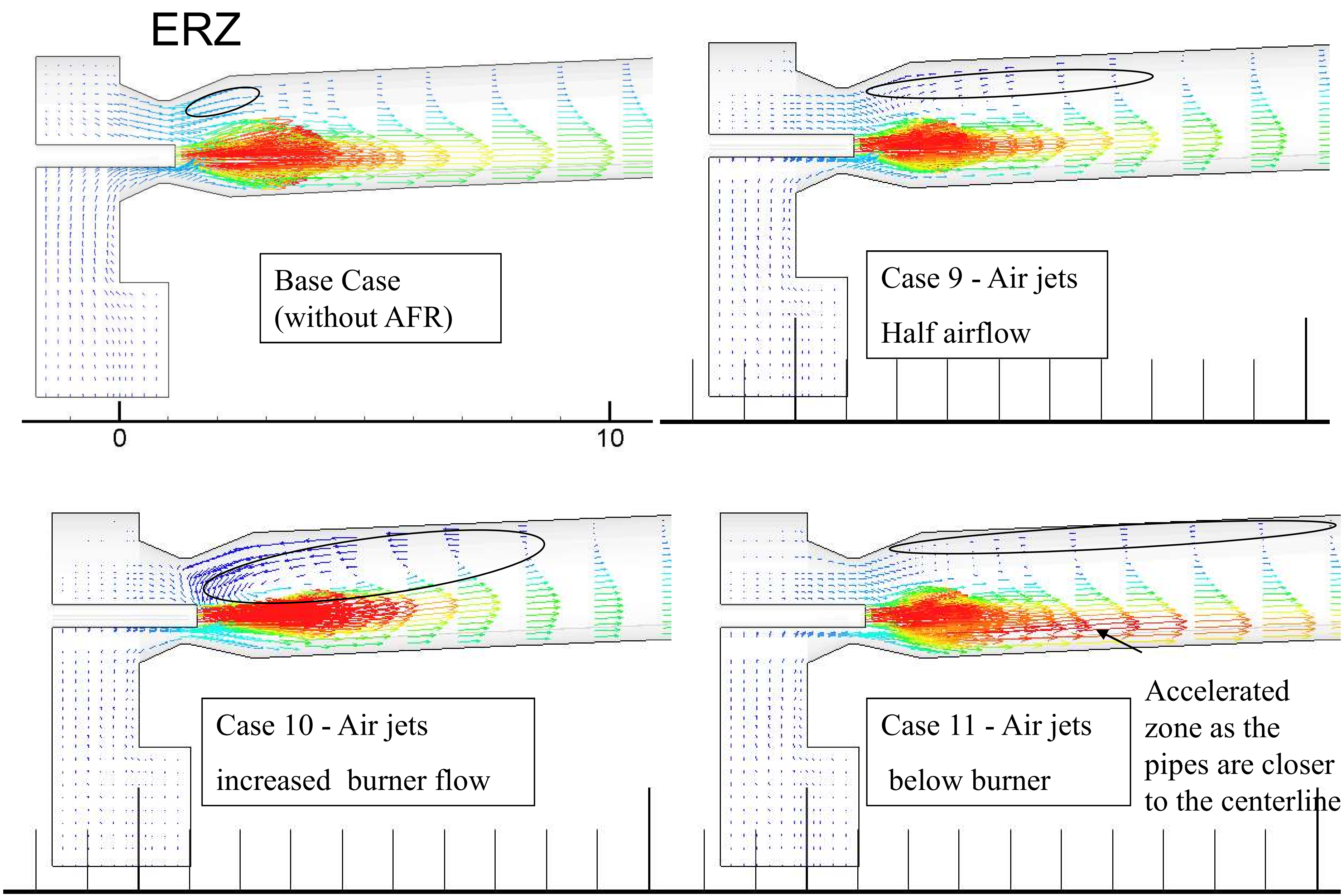

Twin air- jets Arrangement

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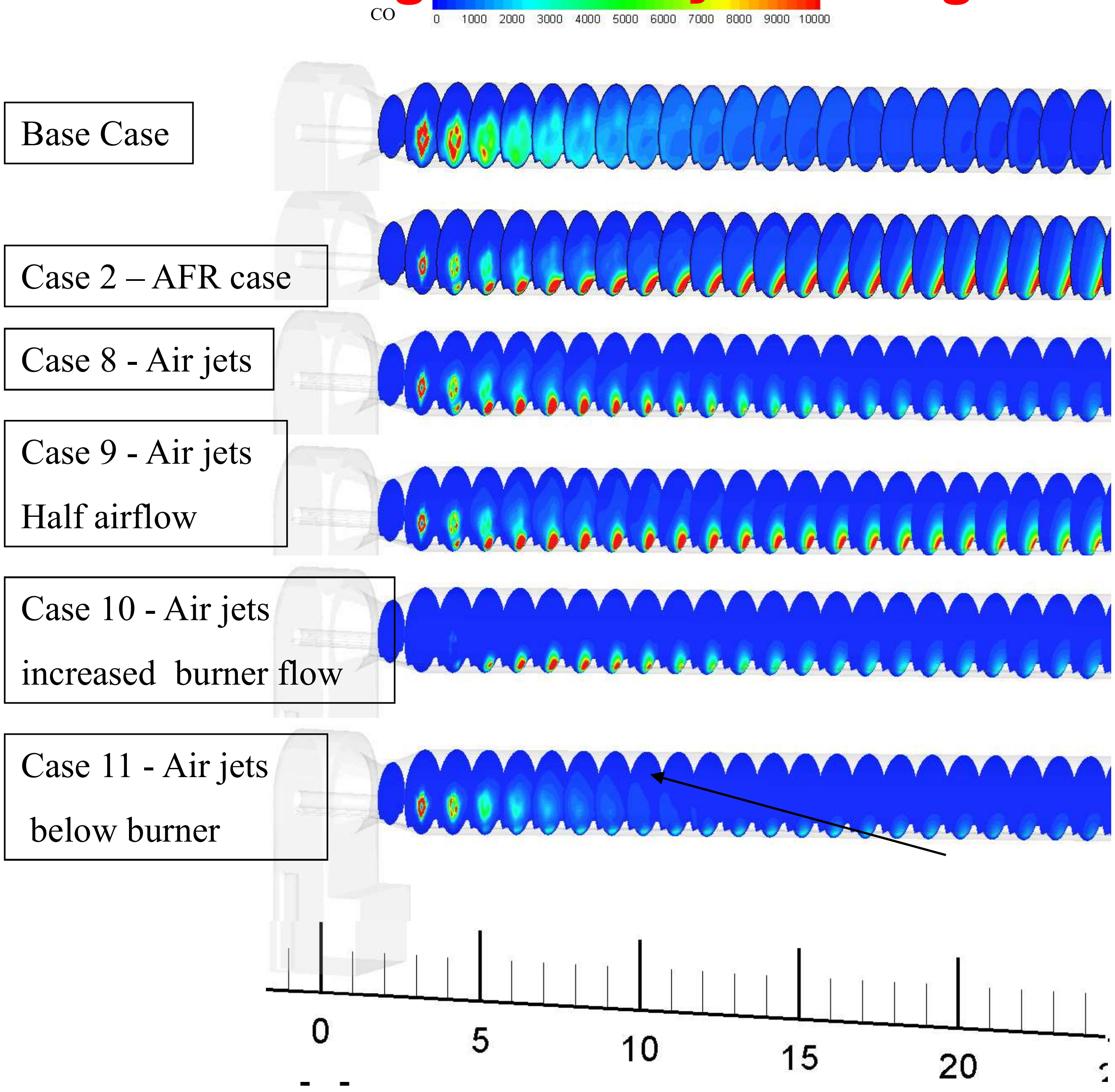
CO Reduction through Twin air-jets Arrangement



Exit CO Values:

94ppm

2133ppm

158ppm

803ppm

261ppm

75ppm

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CO Reduction through Mid-Kiln JAMS Arrangement

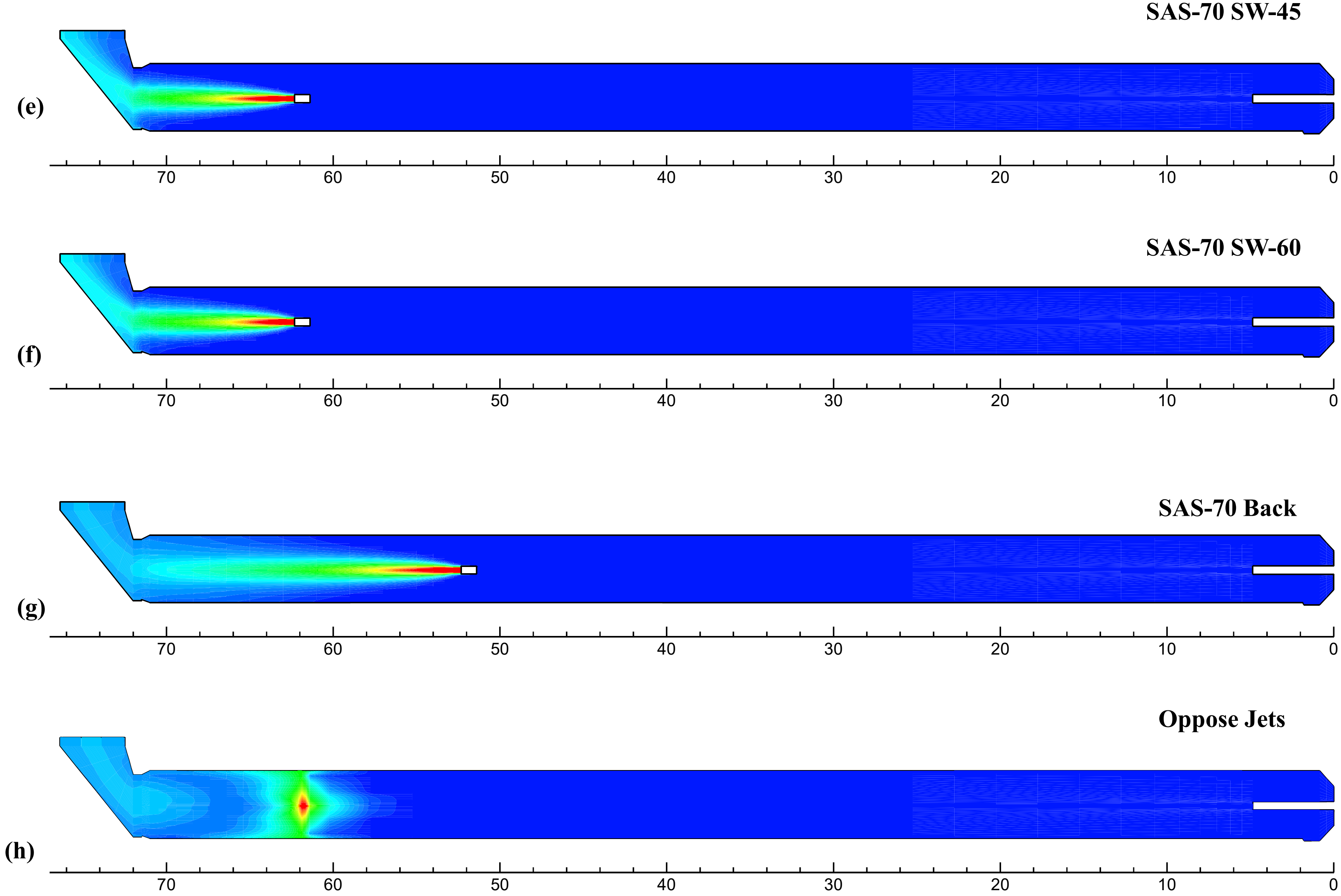

Figure 13: Mixing jet mixture fraction fields

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Calciner Flame (Invisible Flame)



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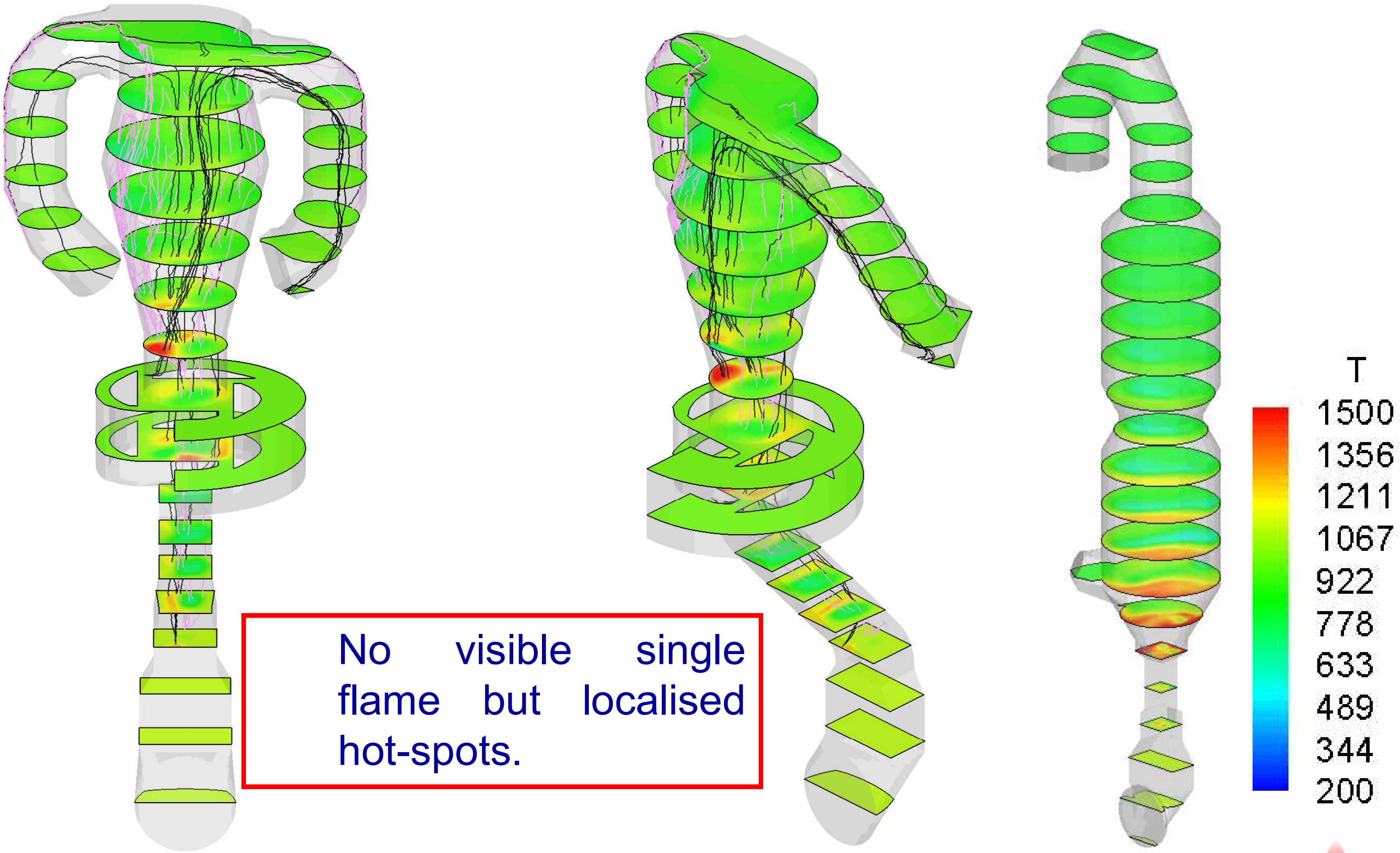
Calciner Flame (Localised Hot-Spots)



No visible single flame but localised hot-spots.

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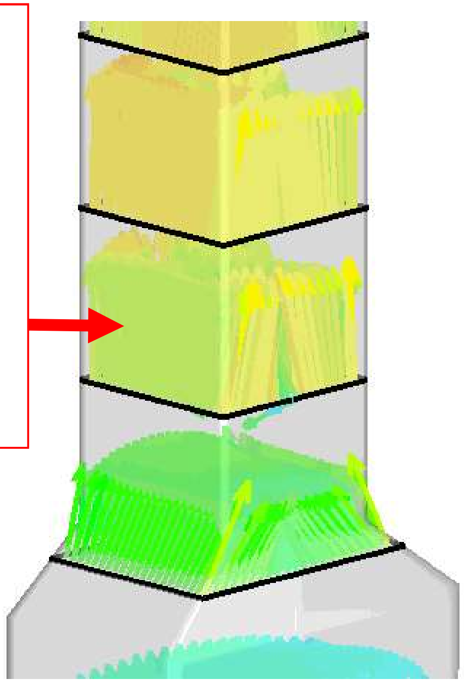
Riser Burner:

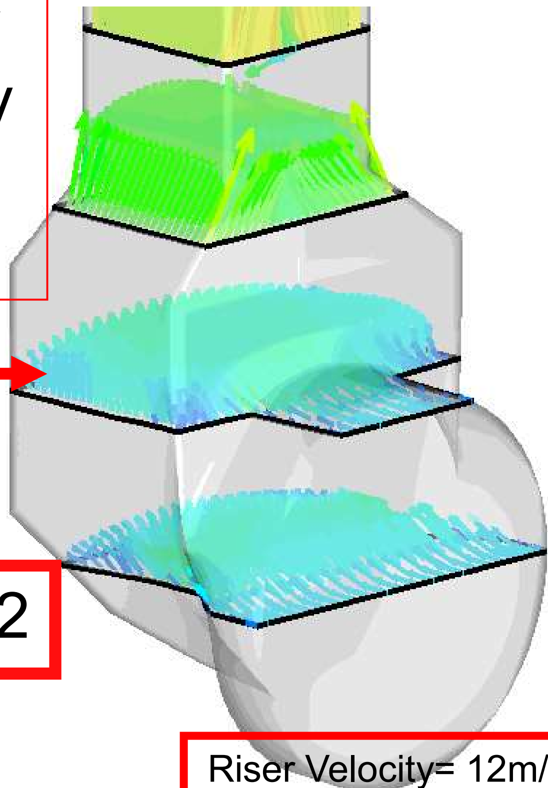
Flow rate: 1.5kg/s; V=60 m/s

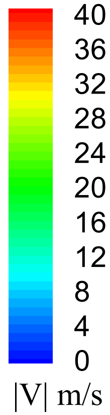


MR= 1:12

Riser flow: 32kg/s; V= 35m/s

Burner Velocity =150 m/s





MR= 1:2

Riser Velocity= 12m/s

Half momentum mixing approach:

(relocating burners/JAMS!)

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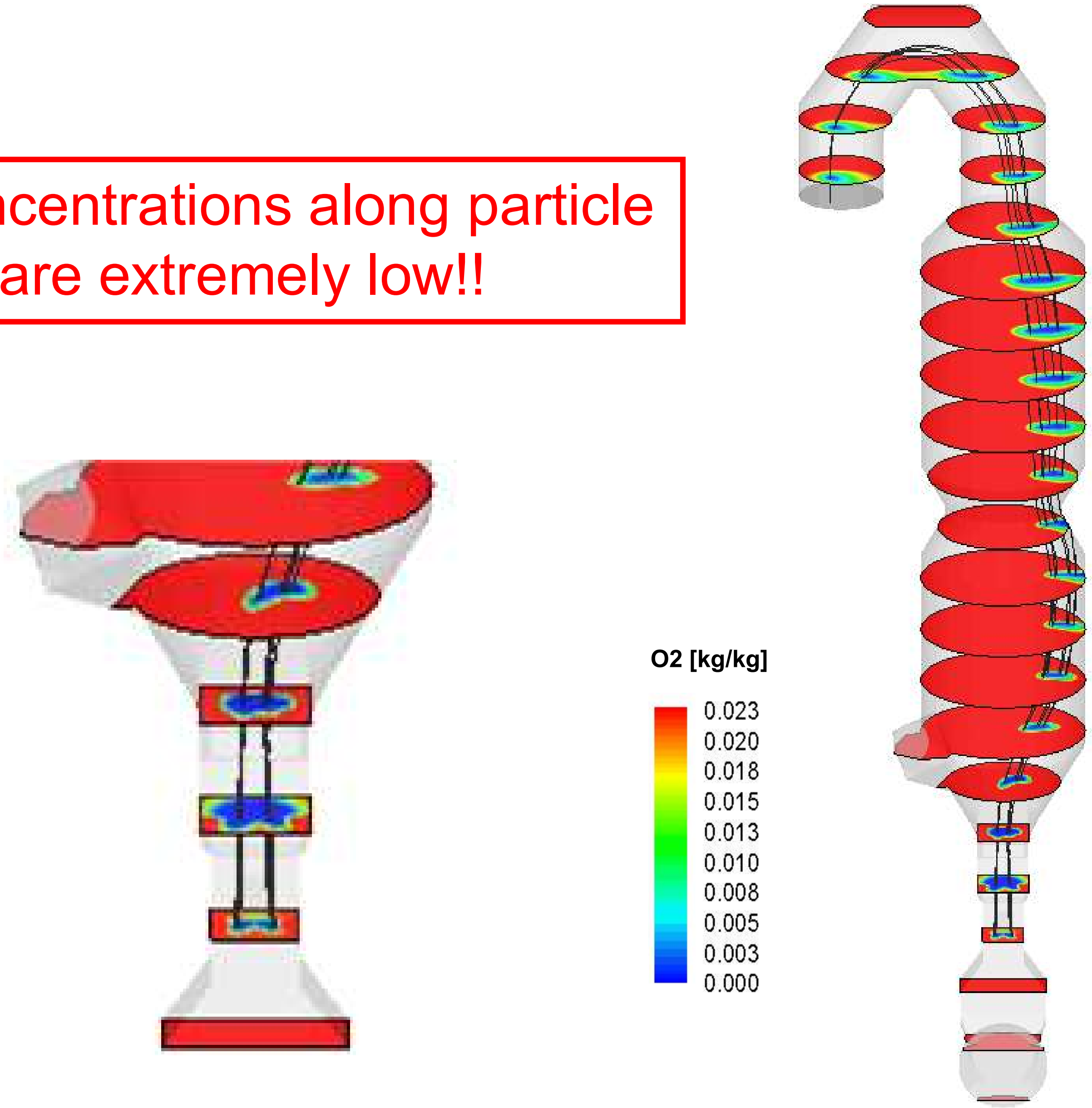
Coal Particles in Oxygen: (Maximum oxygen 2.3%)

Oxygen concentrations along particle trajectories are extremely low!!



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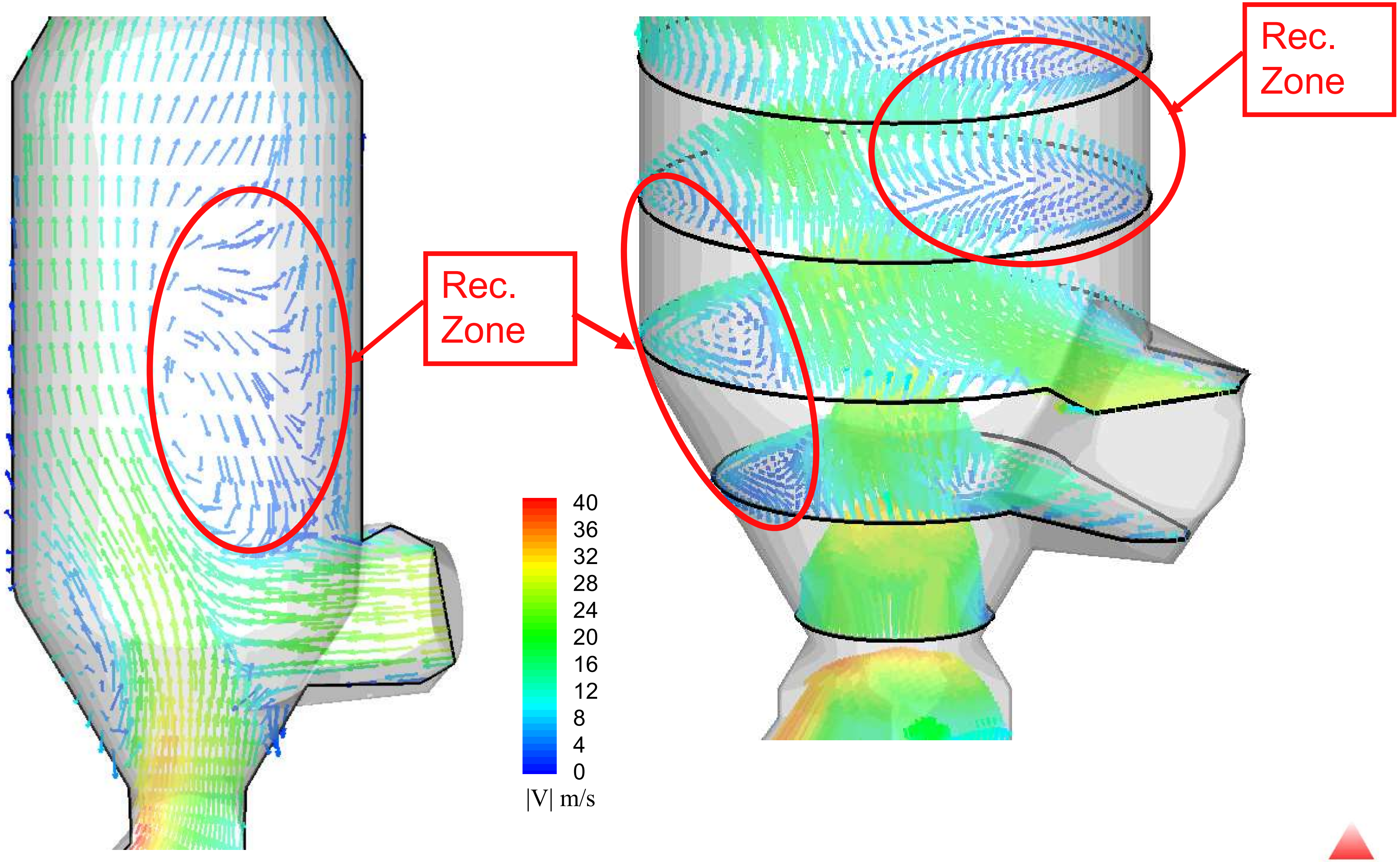
Kiln and TA flow Mixing: Velocity Vectors



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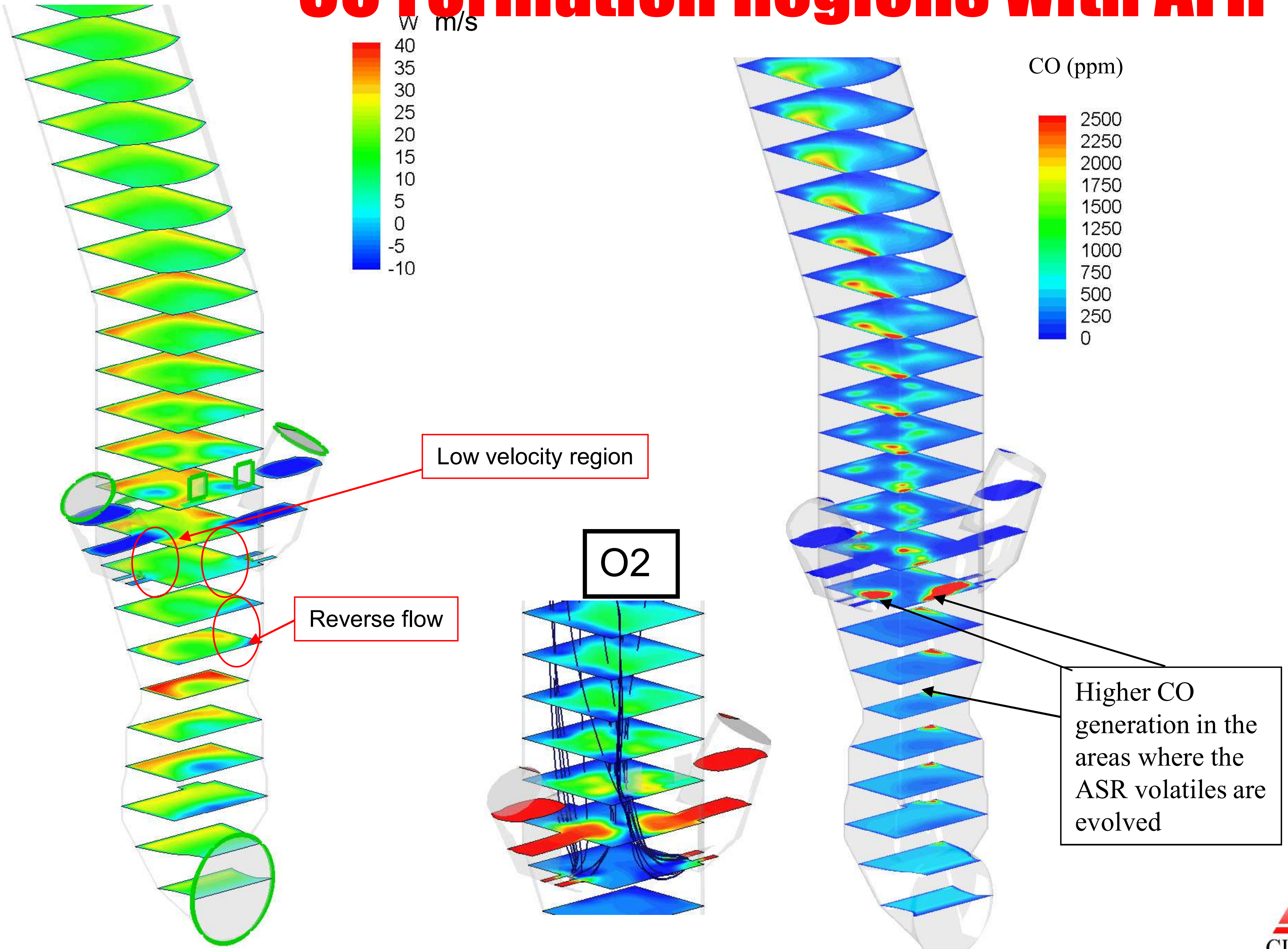
CO Formation Regions with AFR



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Reducing CO-General Comments

Fuel-rich pockets enhance CO formation, more so if fuel volatiles are trapped in the flow recirculation zones;

Improved mixing in hot regions (temperatures above 1000C), in the presence of OH radicals reduces CO at a faster rate;

Improving the residence time alone, away from the NBR (in lower temp. and OH regions; (below 950 C) is less efficient.

If mixing cannot be improved by a simple geometrical alteration, air jets or burners with axial air, having at least half of the momentum of the unmixed stream, may be considered.

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Reducing NOx/CO in Calciner

- Suppressing Air-Fuel mixing:

  Low NOx burner, FGR, flameless oxidation;

  Lower potential for NOx (10-40%), But higher for CO

- Fuel Reburning/Staging:

  Creation of CHi and OH radicals which reduce both NO and CO (kiln generated);

  Higher potential for reducing both (10-80%)

- SNCR/SCR:

  Inject of NH_3 or NH_2CONH_2 @ (900-1100 C)

  Higher potential (10-80%)

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The Most Important Variables for Reducing NOx:

Temperature;

Residence time;

Fuel volatile/nitrogen content;

Stoichiometry conditions;

Volatiles/Riser Gas & Volatiles/TA mixing!

Case Studies!

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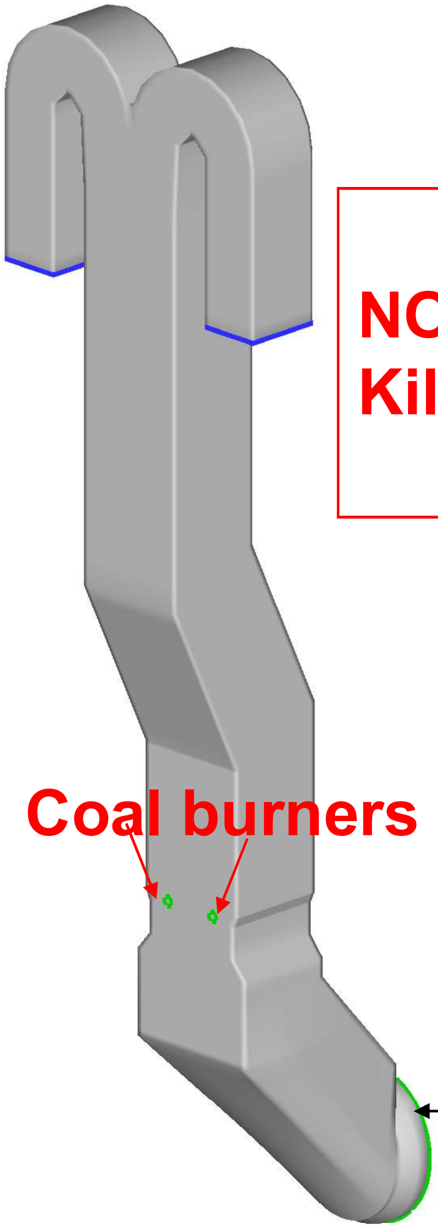
Reducing NOx Emissions
in an AT Calciner
(RT =1.5 s)

NOx Reduction in an AT Calciner

Further NOx reduction potential: 30-35%



Calciner Exit

NOx: 371

Kiln NOx reduction: 45 %

Kiln Inlet

KBE O2 : 9.9 %

NOx: 670 ppm

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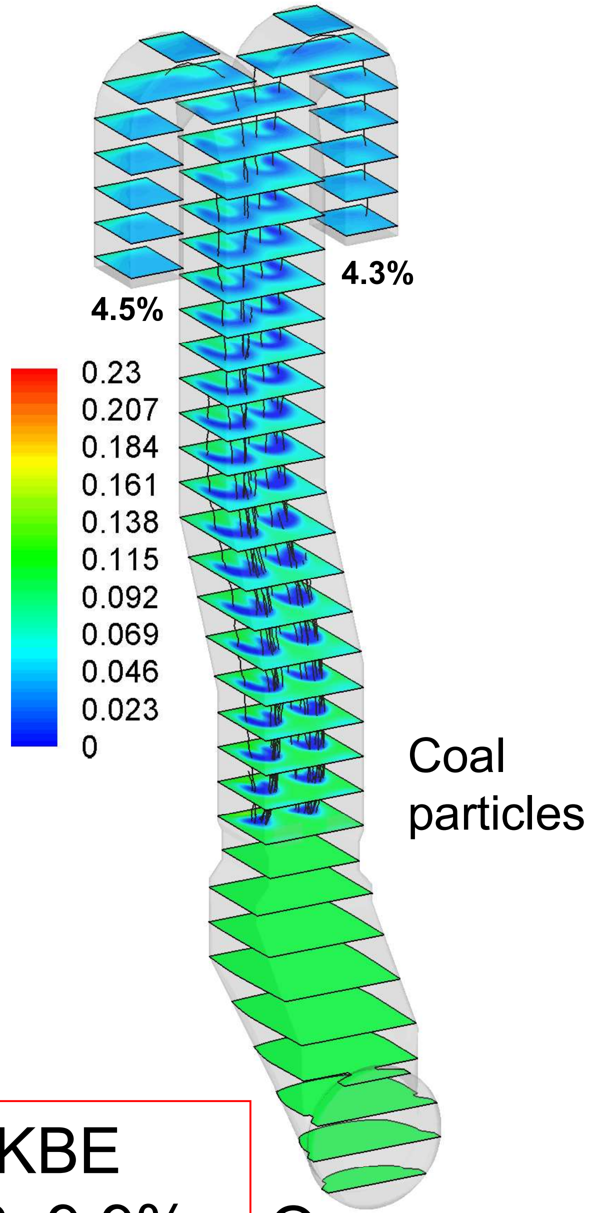
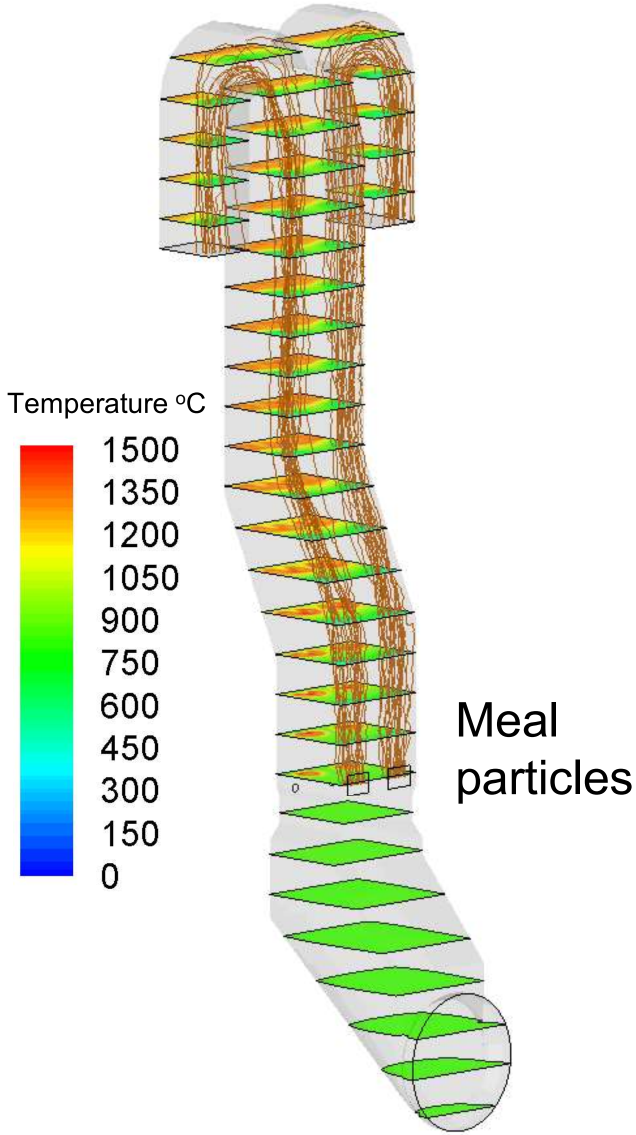
Oxygen & Temperature Profile



KBE
O2=9.9%

Oxygen



Temperature

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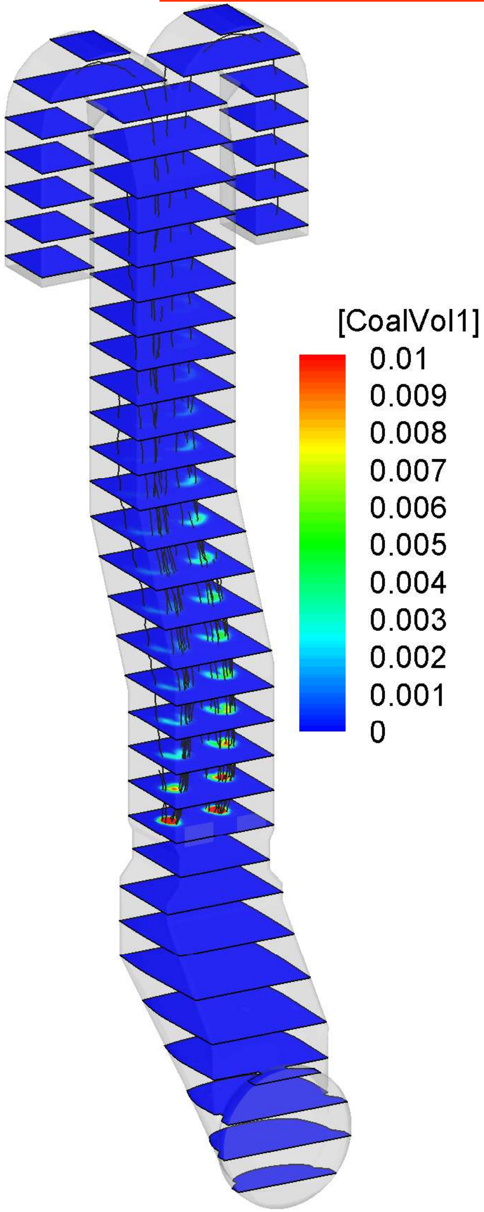
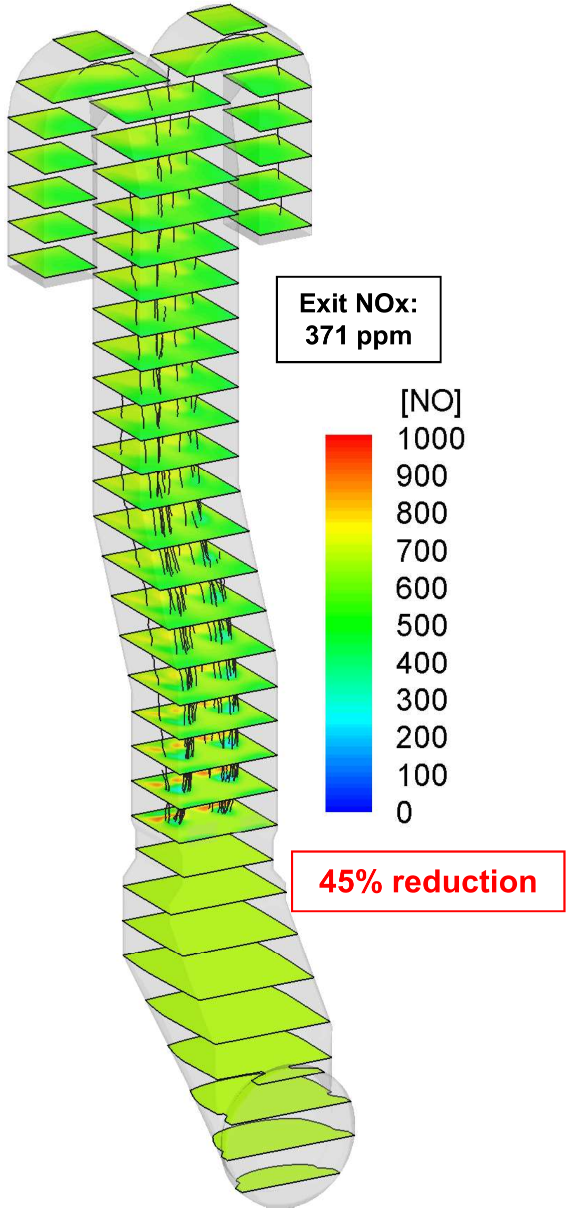
Coal Volatiles – NOx (ppm) & CO (ppm)

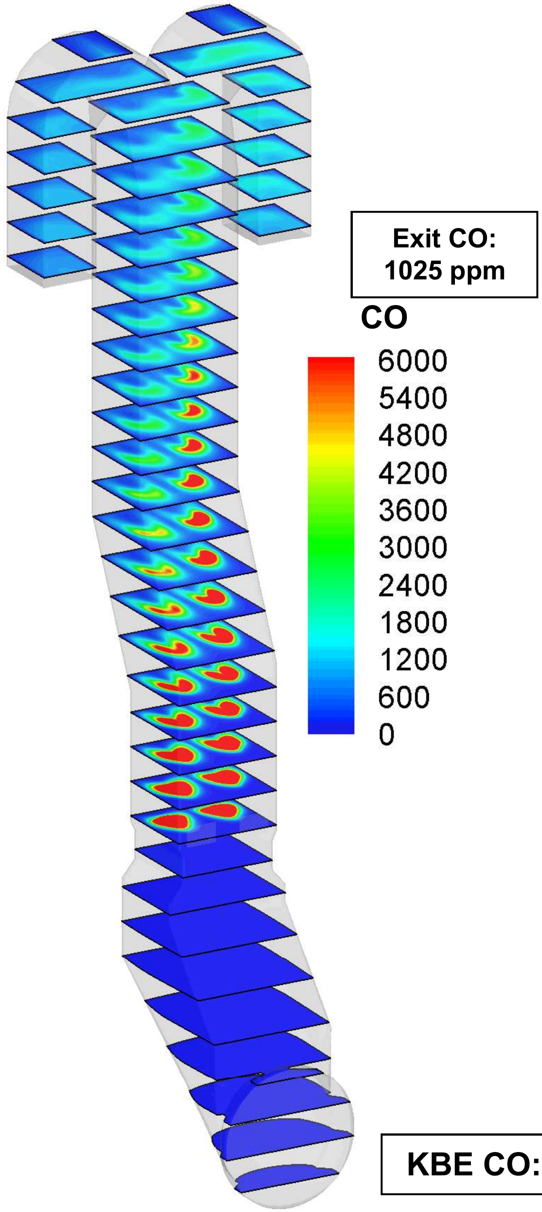


Coal Volatiles



NOx

KBE NOx: 670 ppm



KBE CO: 0 ppm

CO

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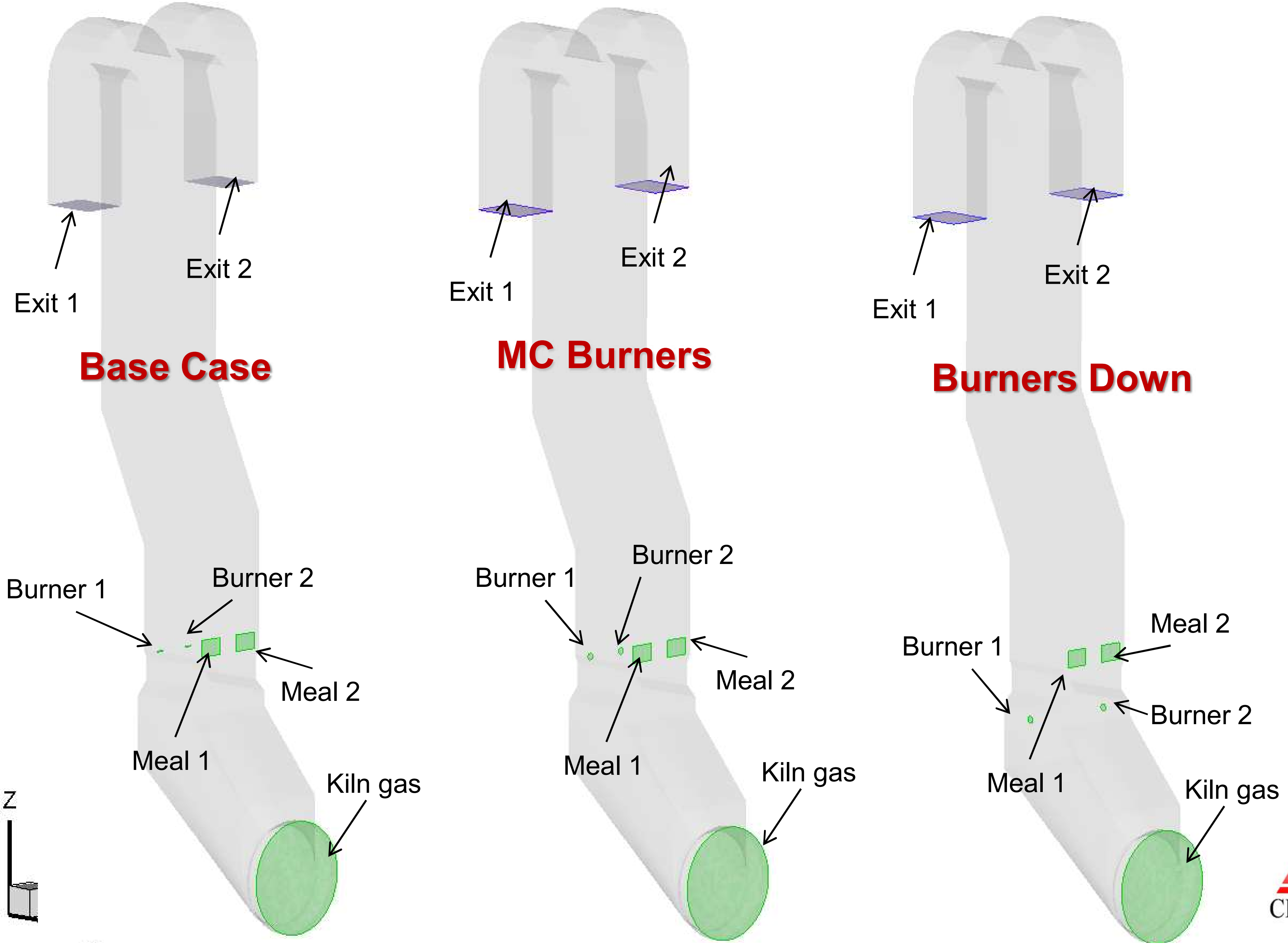
First Priority: Calcination & Burnout



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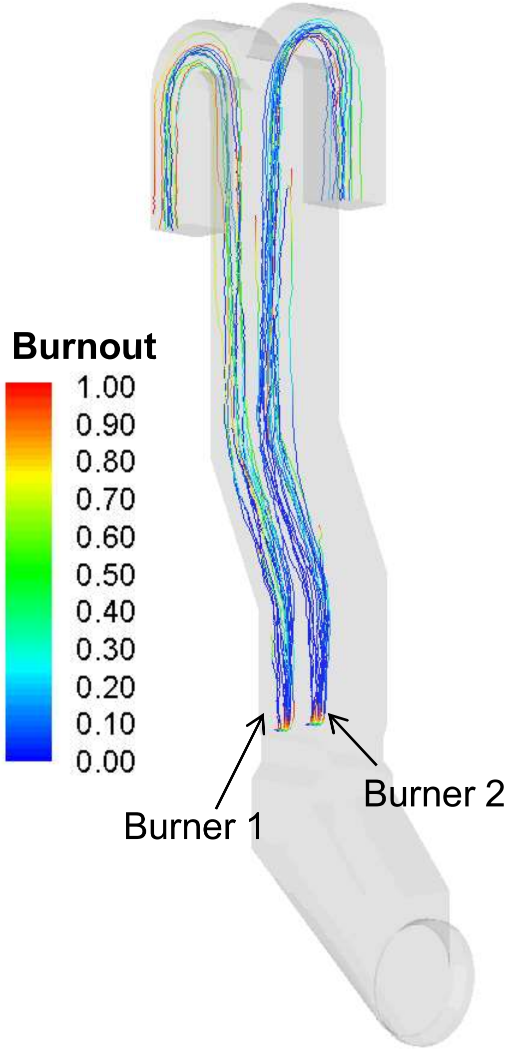
Fuel Particles and Burnout

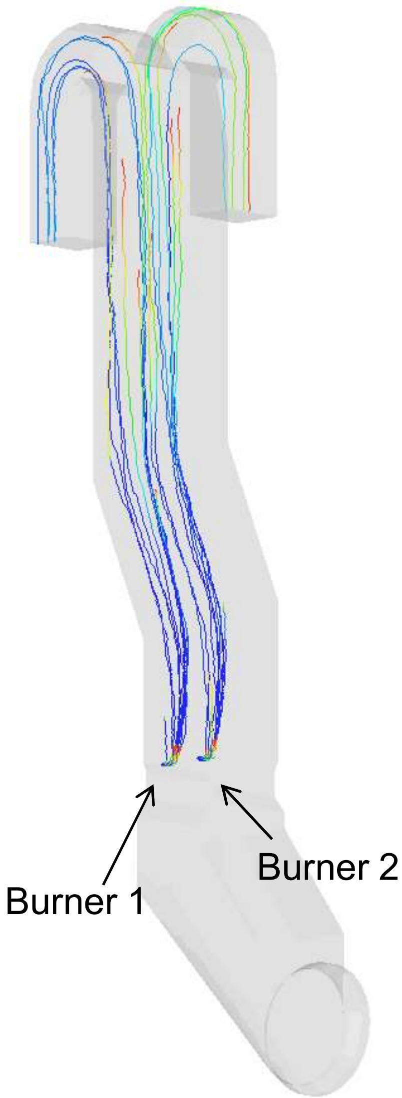
Base Case

Burnout: 80%



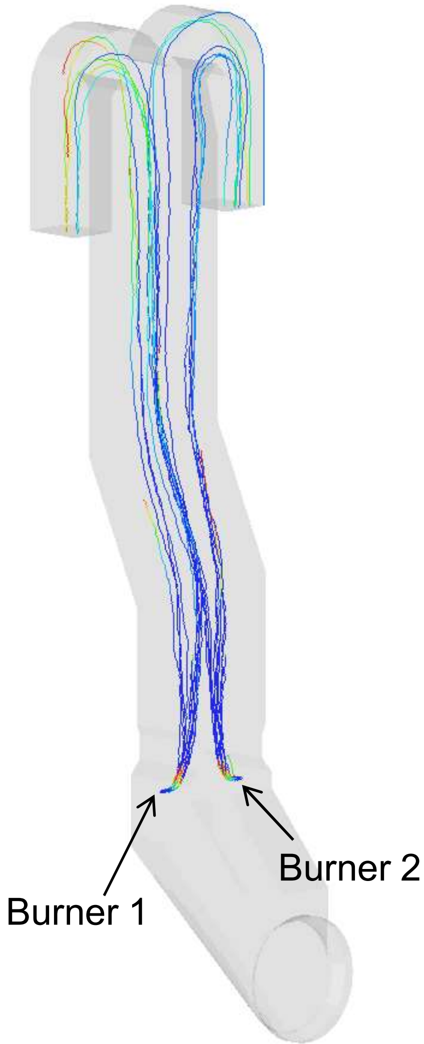
MC Burners

Burnout: 91%



Burners Down

Burnout: 93%



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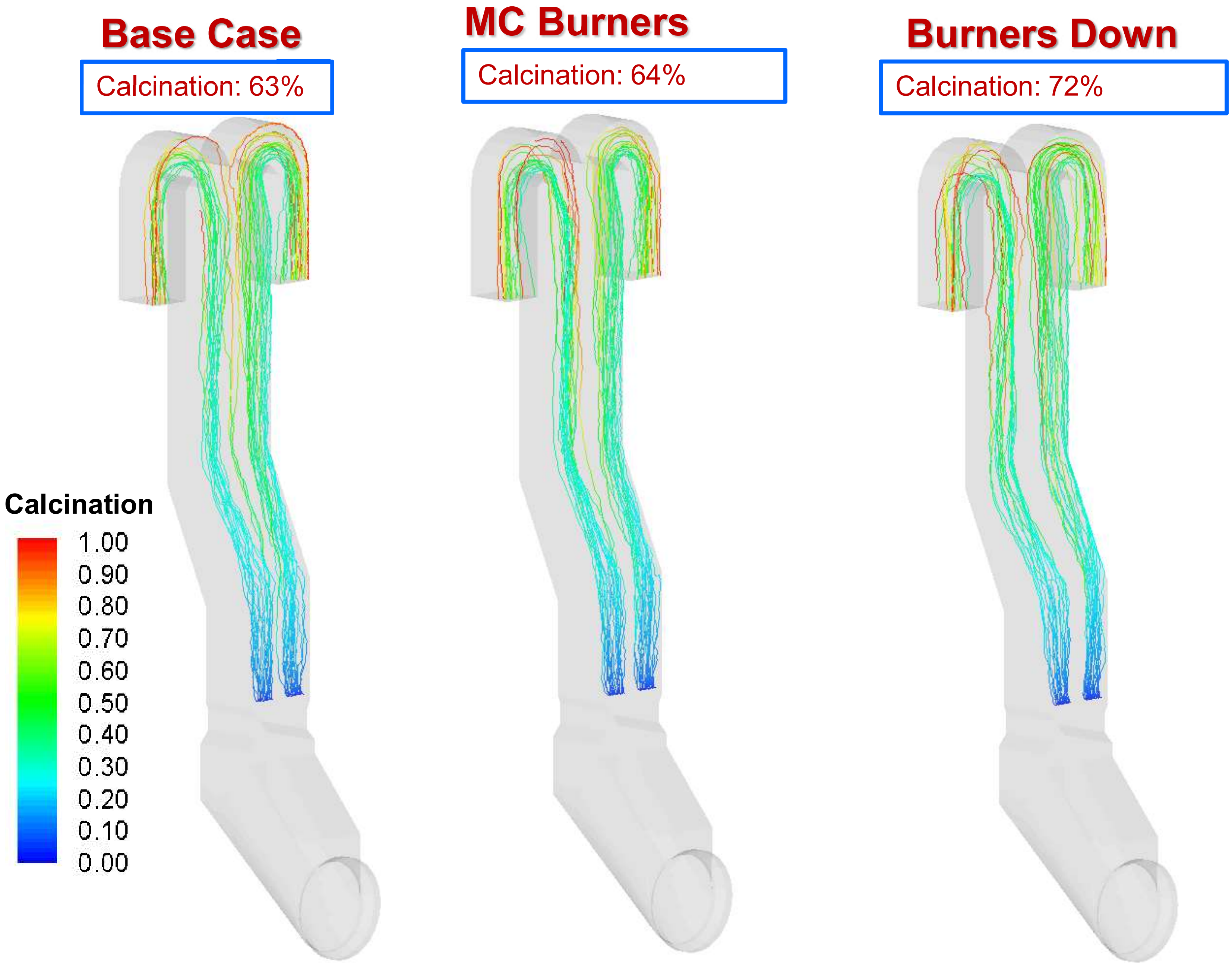
Meal Particles Tracking



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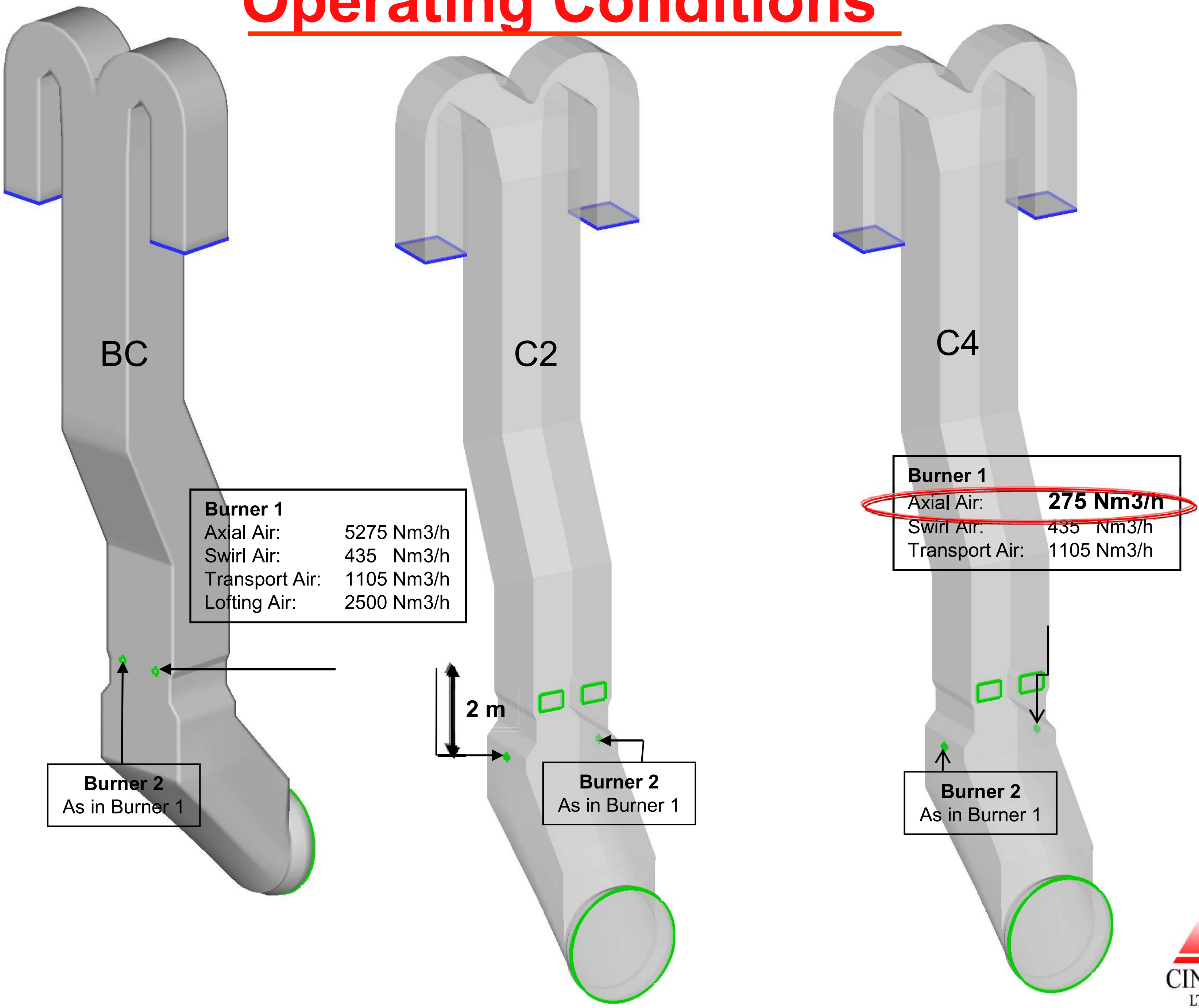
Operating Conditions



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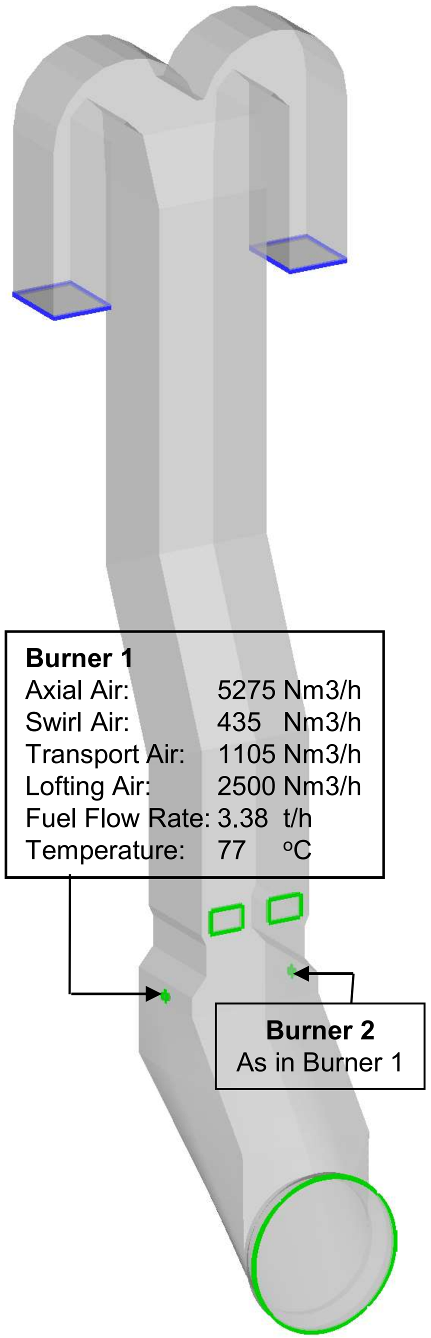
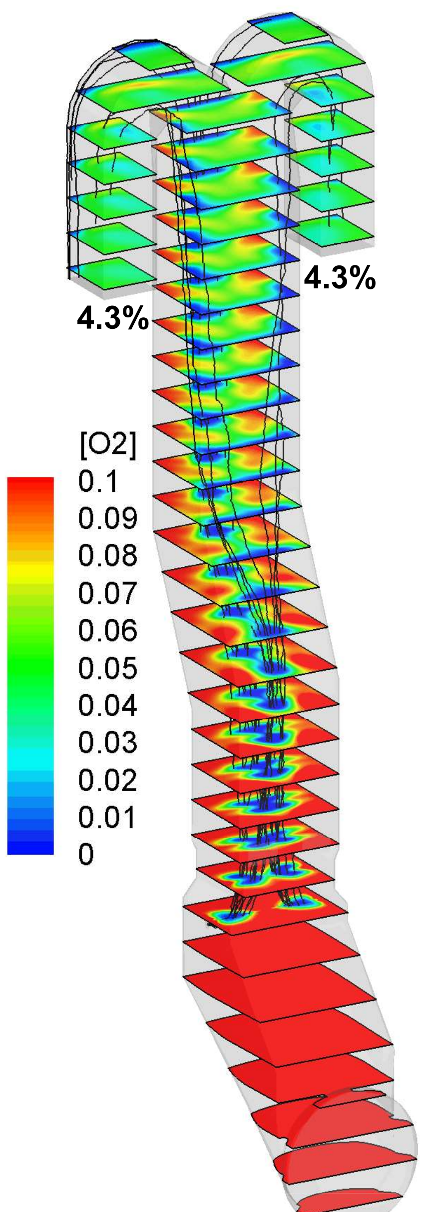
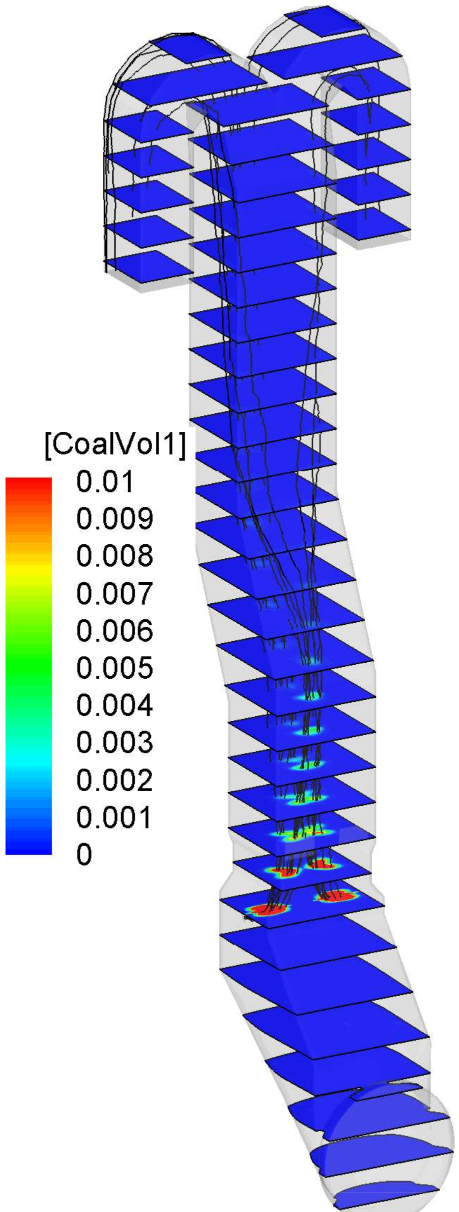
Case 2: 10% KBEO2, 2 Lower Burners (2m-From MC Burner on side walls)





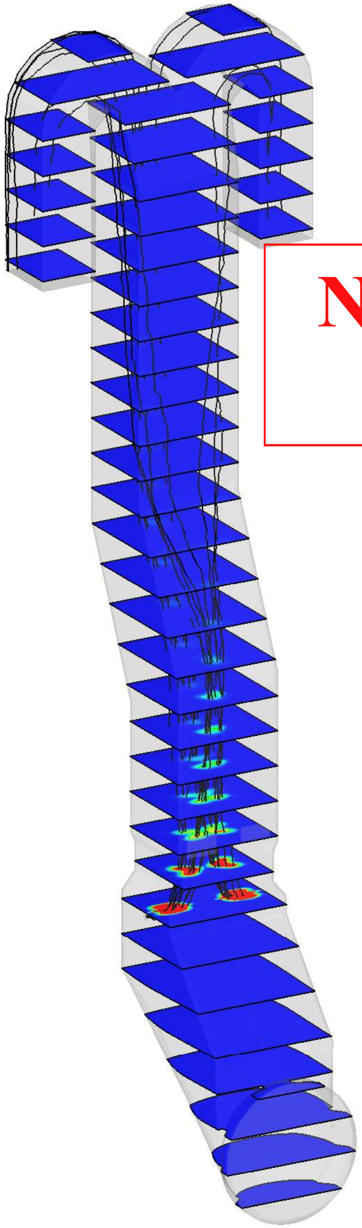
Oxygen



Coal Volatiles

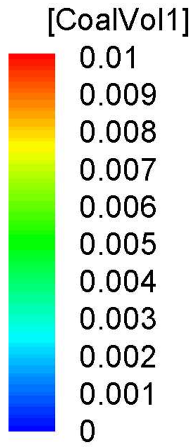
10 % NOx Reduction

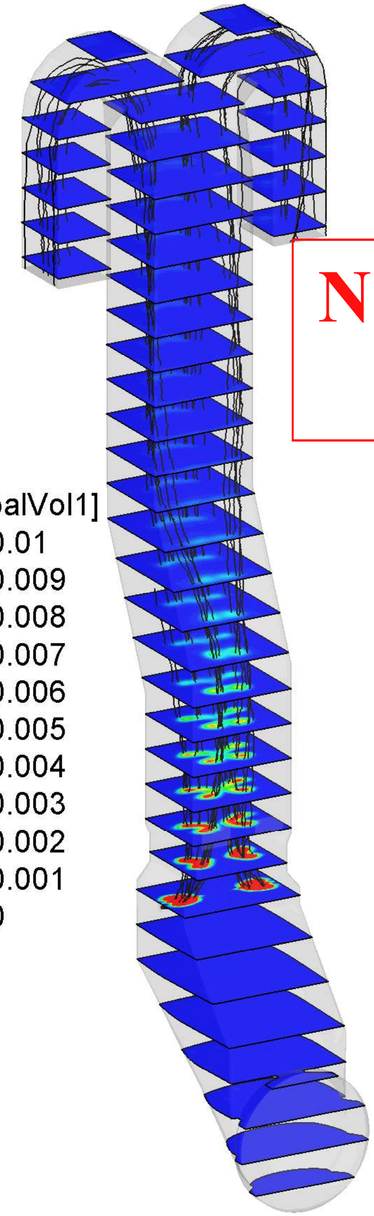
Coal Volatiles



NOx Reduced
10 %

Case 2:





NOx Reduced
16 %

Case 4 (Less Axial Air)

Implementation of JAMS

Two JAMS: (Jet Air Mixing System)

55947 Nm3/h at a distance of 5m above the original MC burners on the side walls with 150 m/s velocity.

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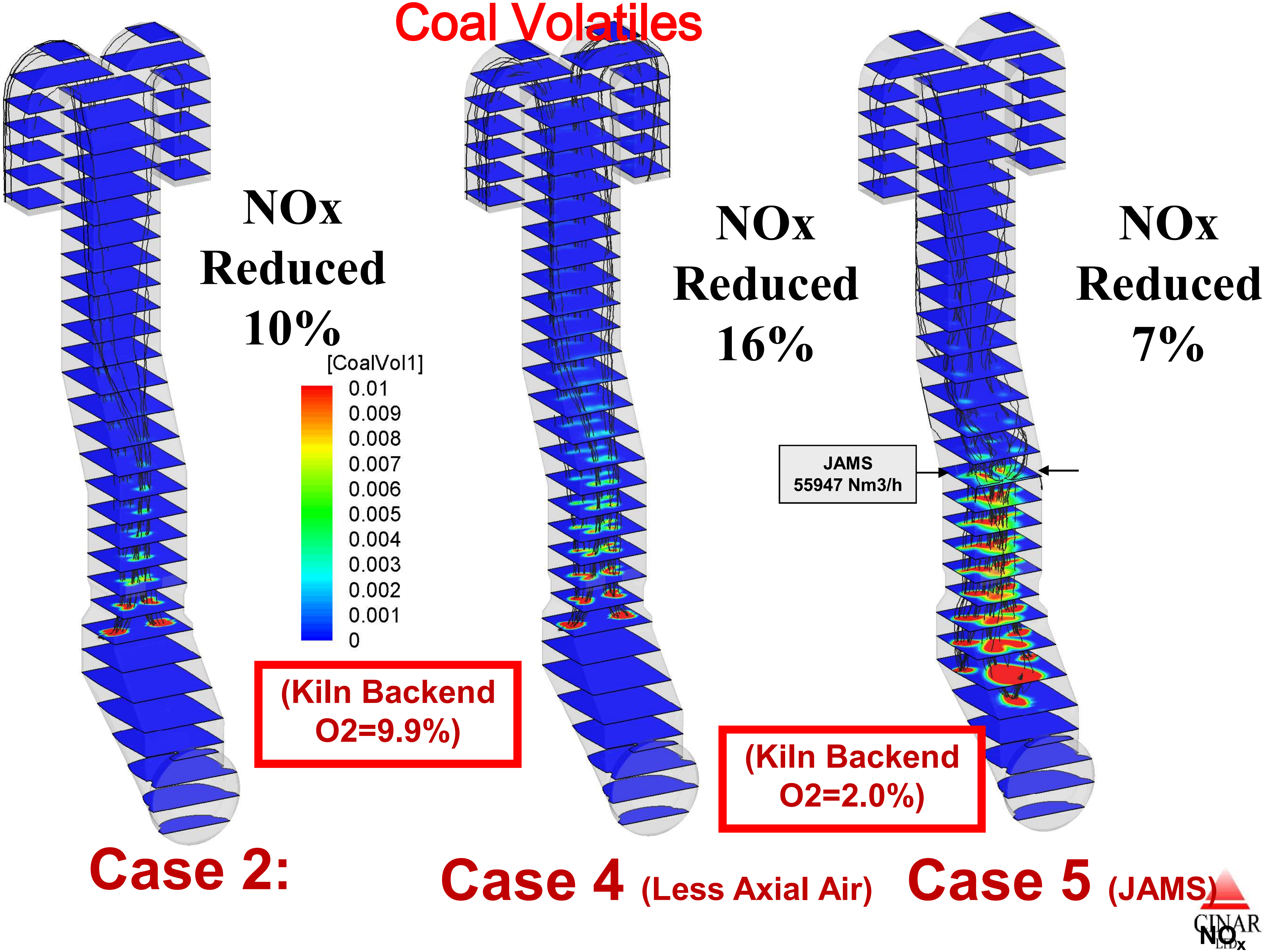
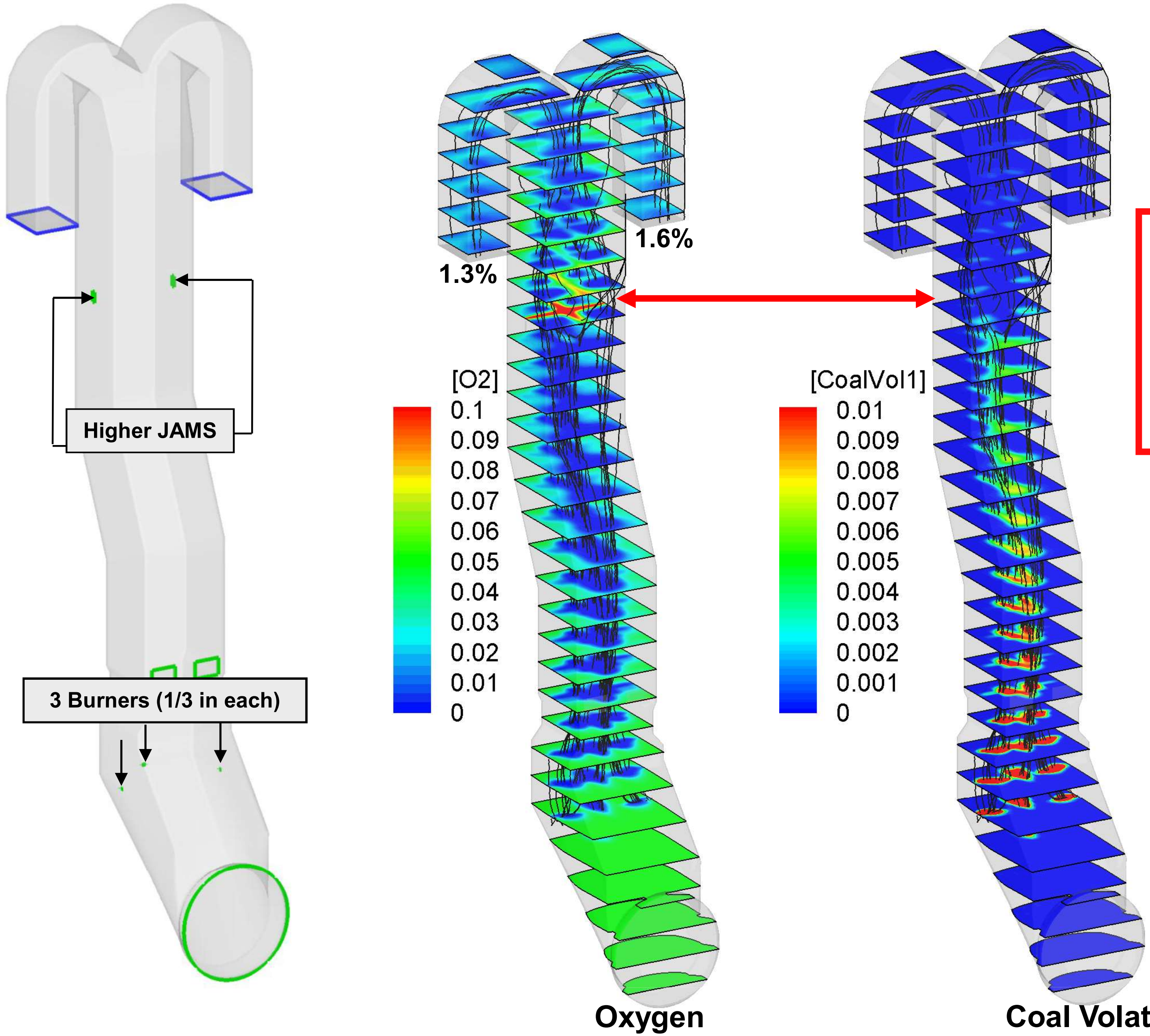
Coal Volatiles

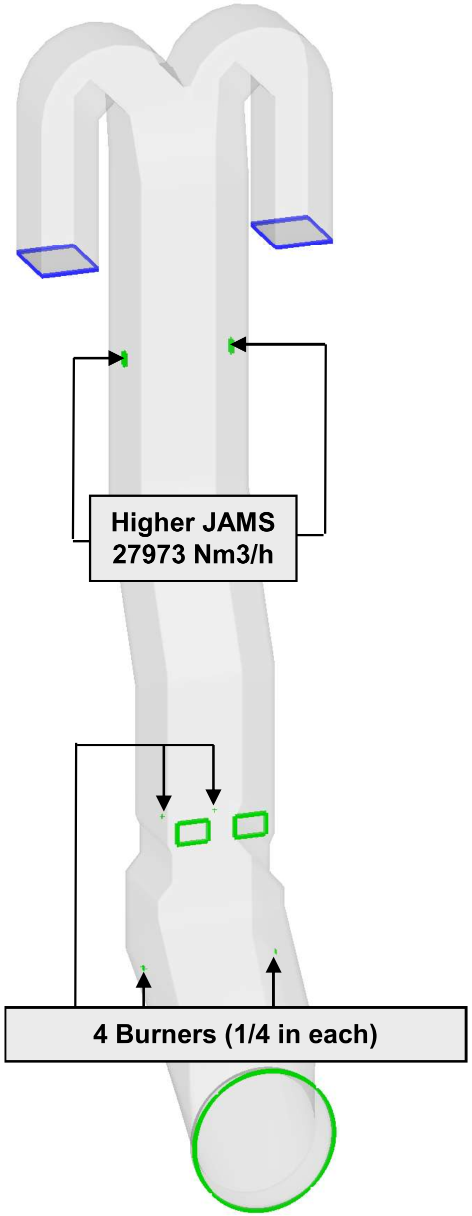


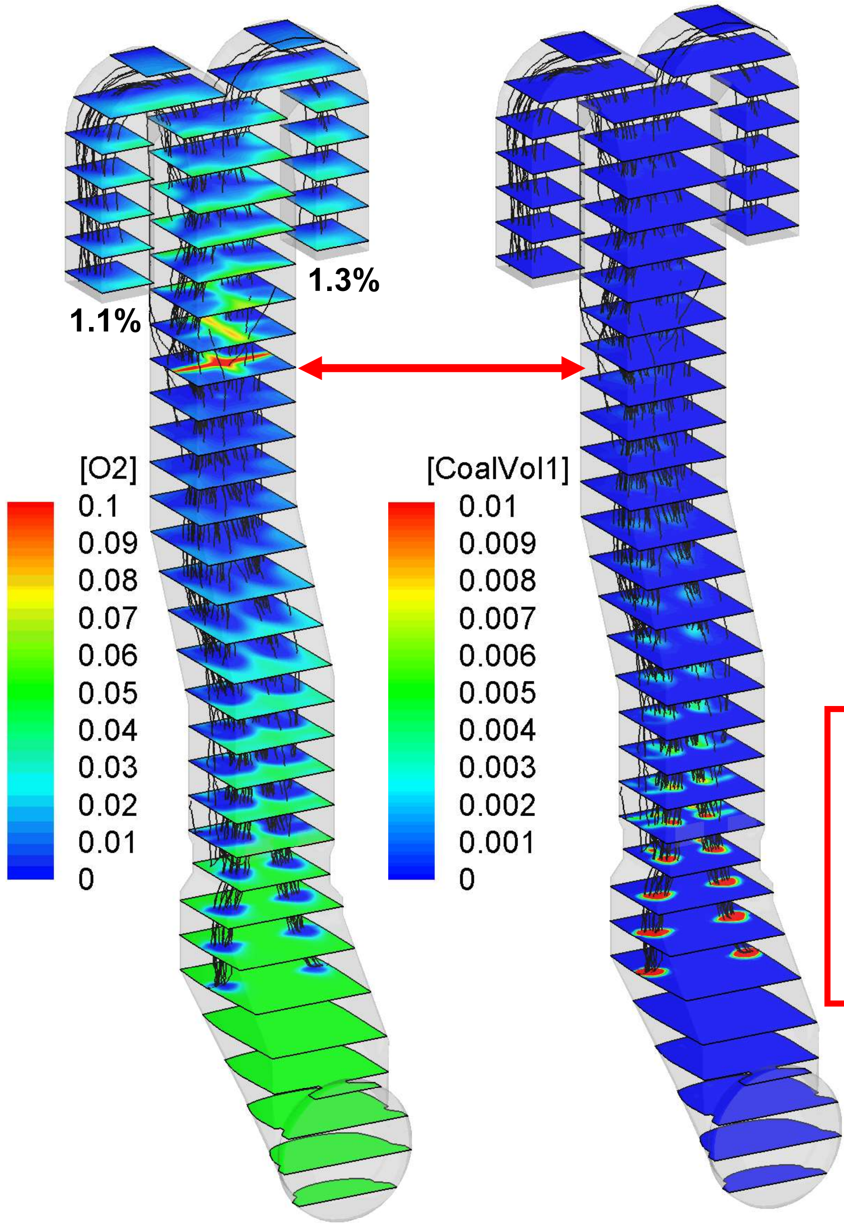
Case 8: JAMS Moved Up (From 5 to 19m above)



NOx Reduced 28%

Case 10: Upper JAMS (4 burners)





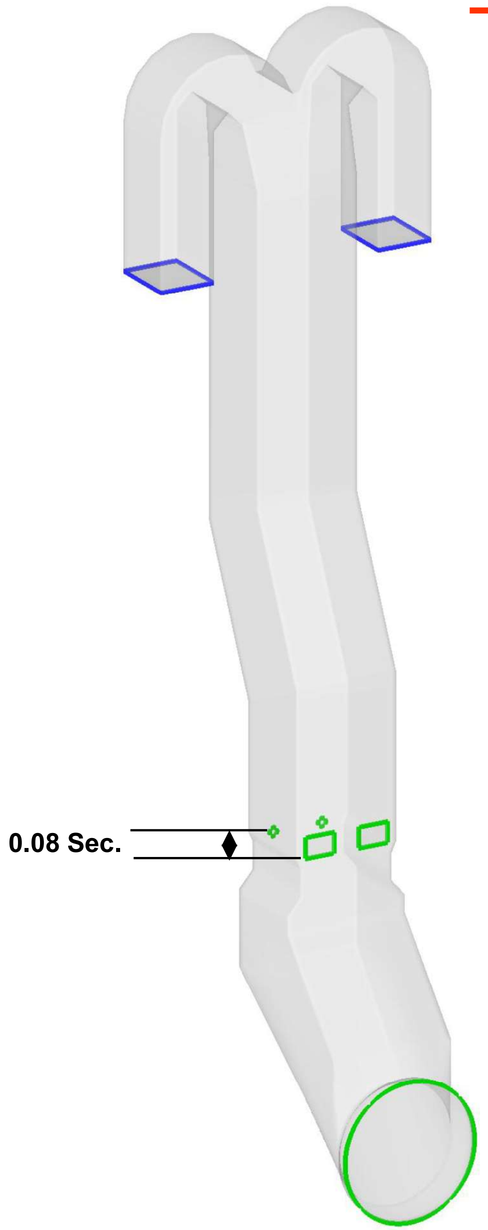
Oxygen

Coal Volatiles

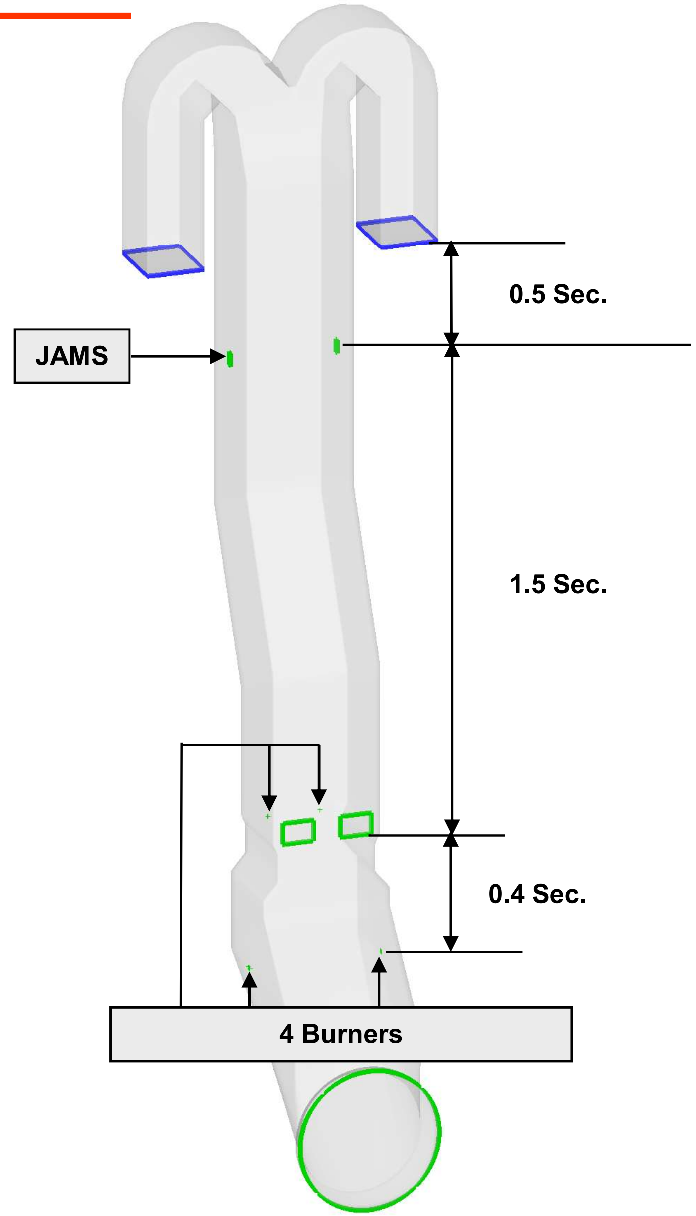
NOx Reduces by 33%

CO Increases correspondingly due to lower RT!

Residence Time



Base Case



Case 10

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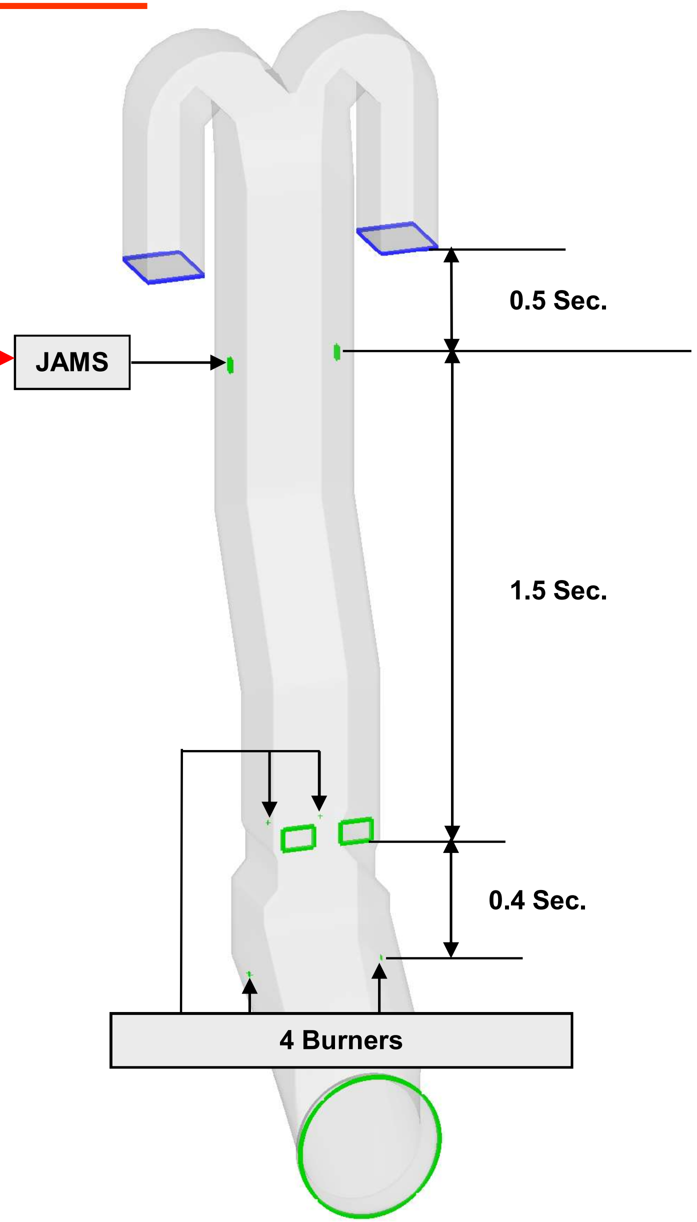
Residence Time

Additional 12,000 Nm3 of air for the JAMS over the 18,000 Nm3/hr already being supplied to the system from the multi-channel burners, will add an estimated fuel penalty of < 10 kcals/kg



Case 10

Important Variables:

- Num. of burners,
- Location of burners with respect to JAMS
- Coal Volatile content

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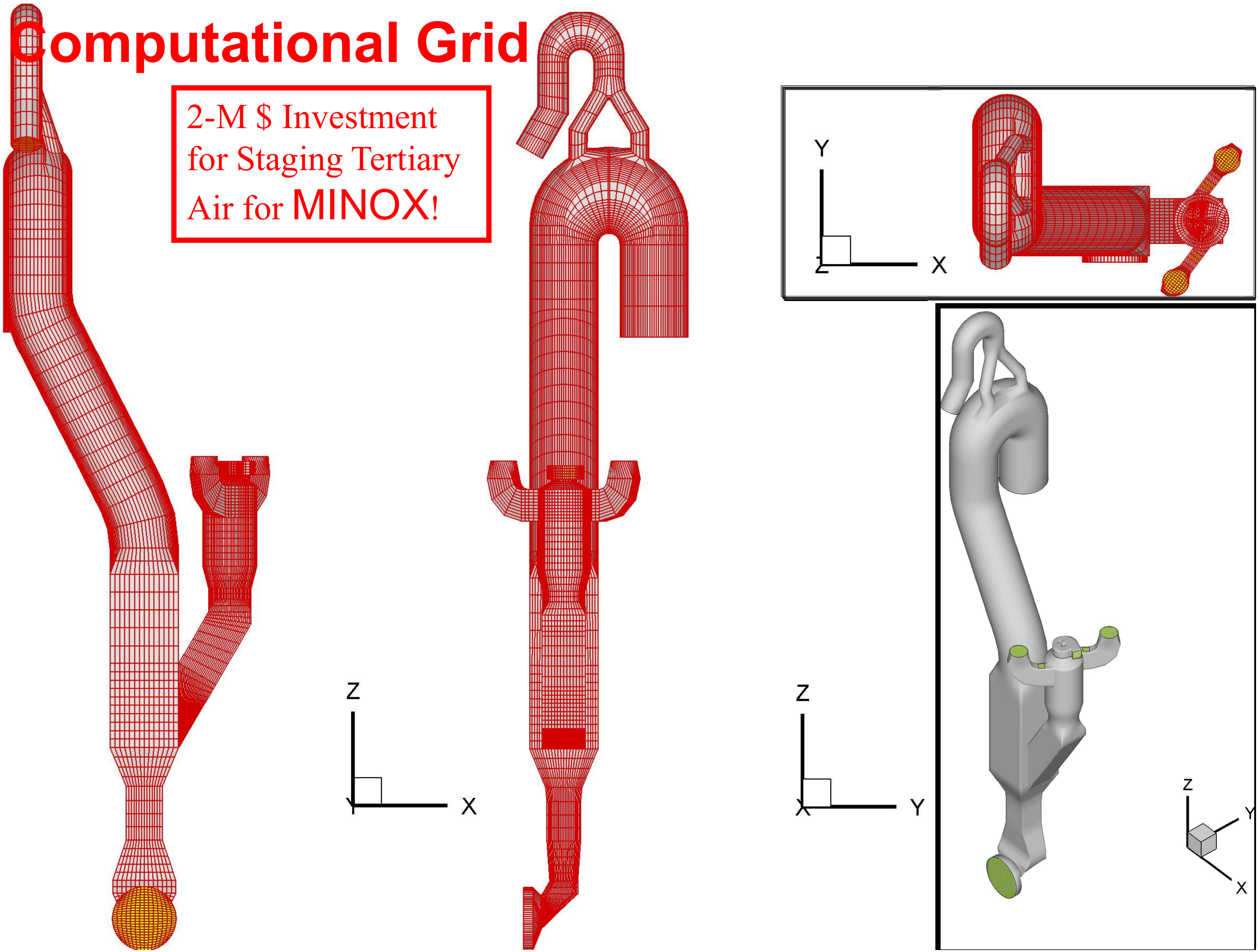
Reducing NOx Emissions

in a RSP Calciner

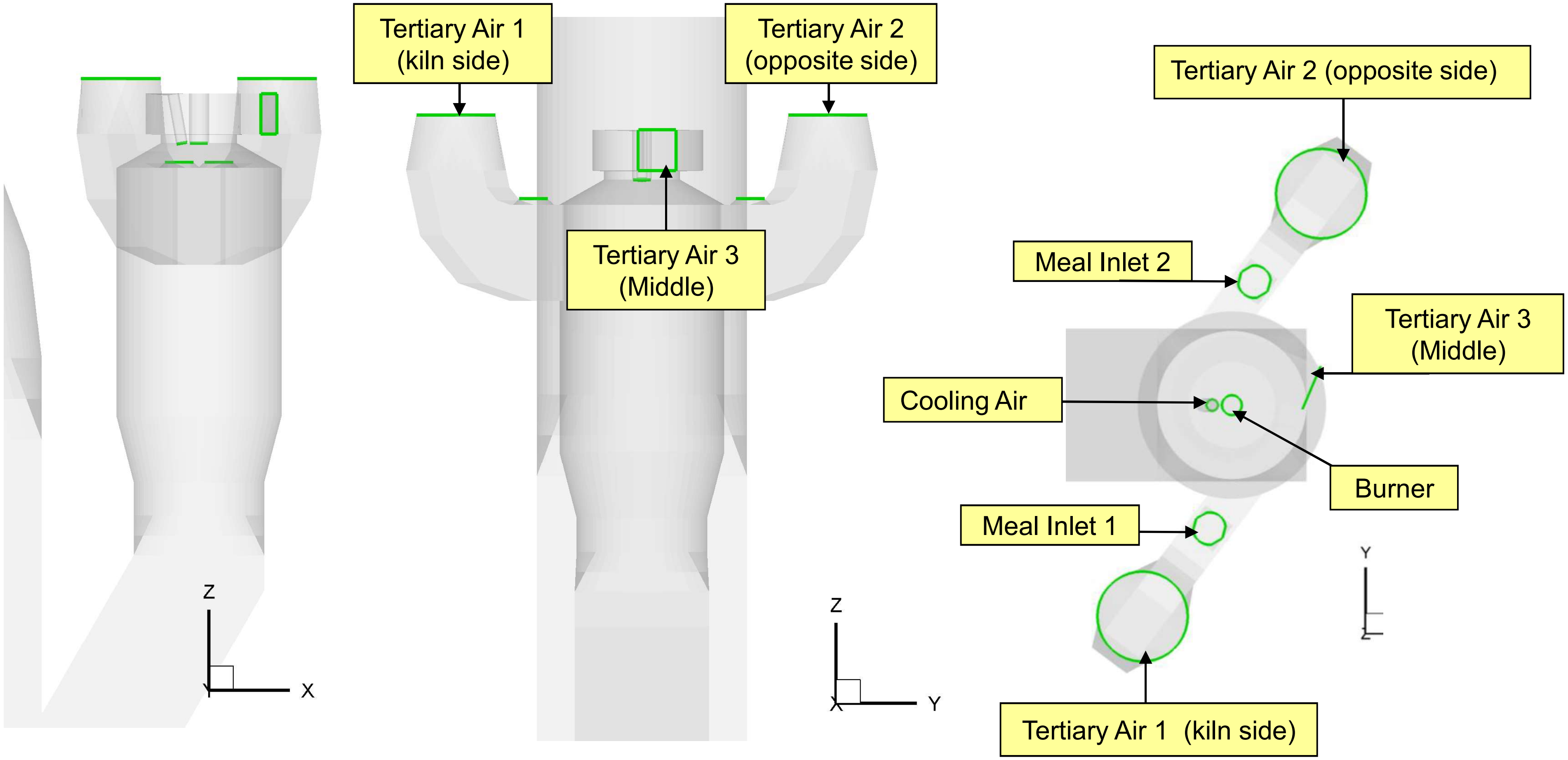
(RT = 5 s)

Computational Grid

2-M $ Investment for Staging Tertiary Air for MINOX!



Swirling Chamber Inlets



Coal-petcoke mixture: 80-20%

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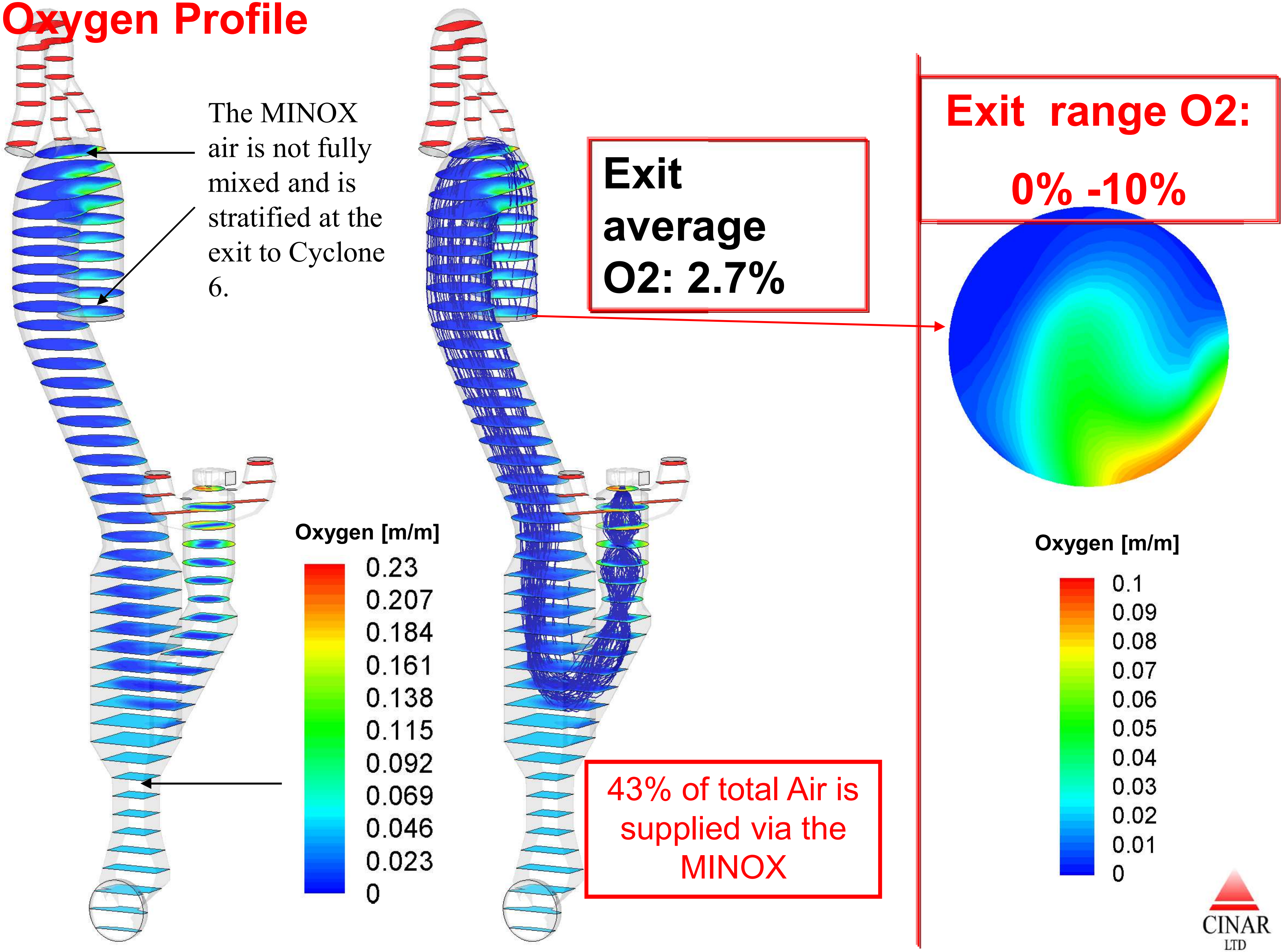
Oxygen Profile



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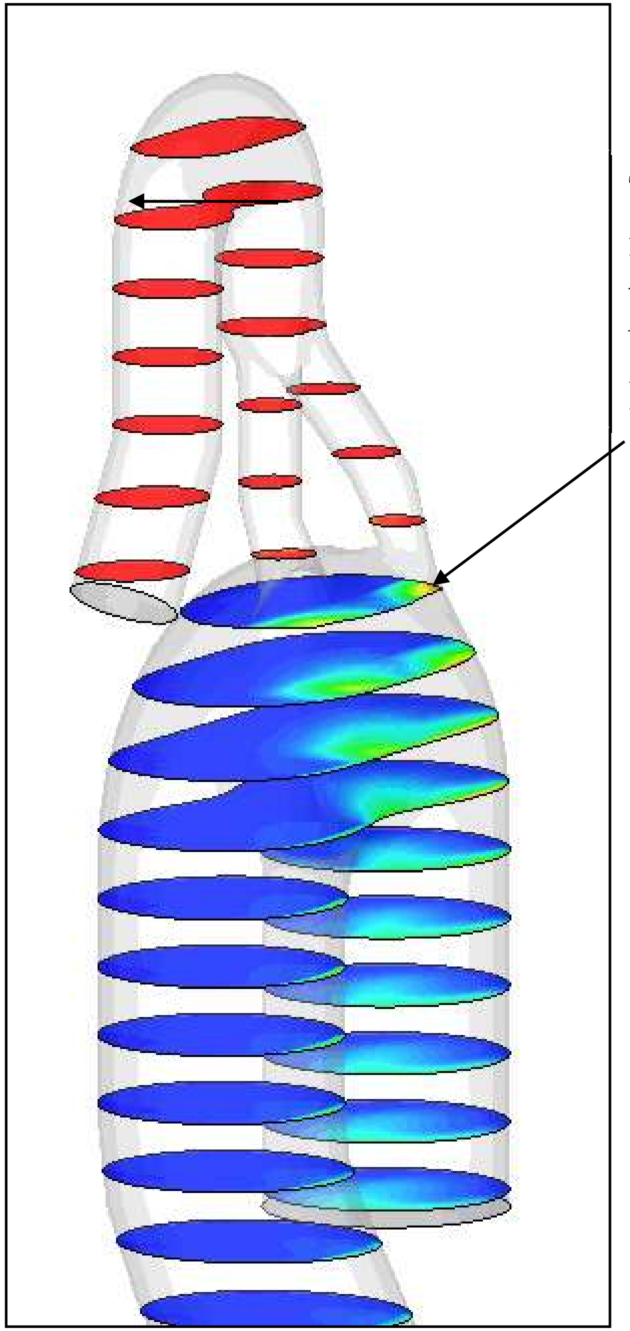
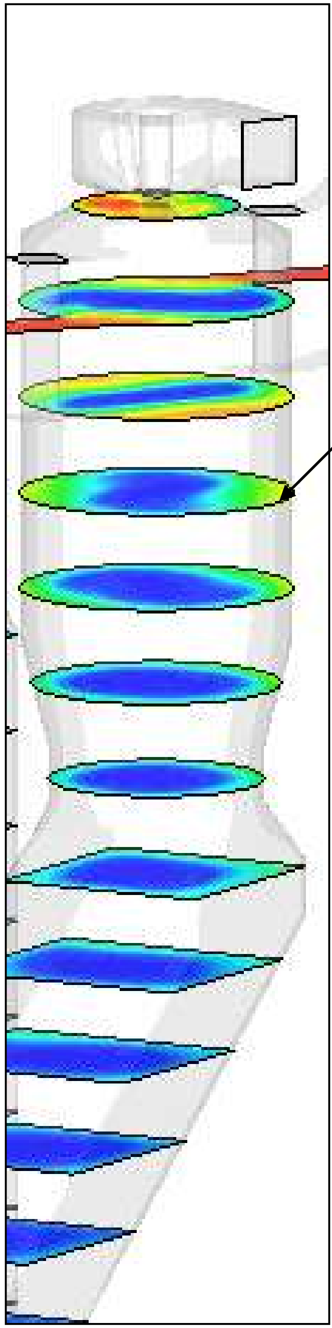
Oxygen Profile



The MINOX air is introduced at the top of the bend at two locations.



In the Swirling Chamber most of the remaining O2 is found on the periphery, where the fuel particles are not travelling.

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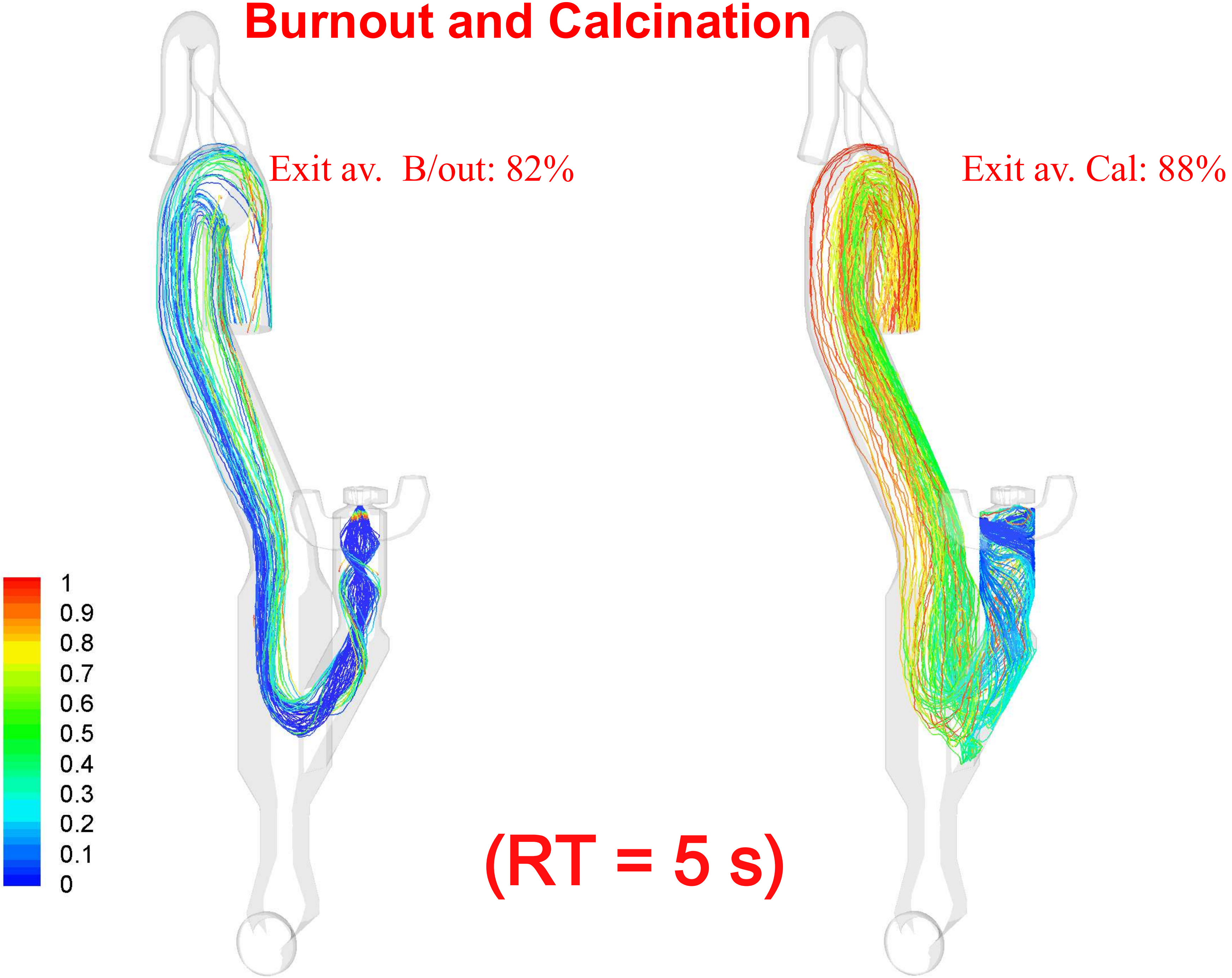
Burnout and Calcination



(RT = 5 s)

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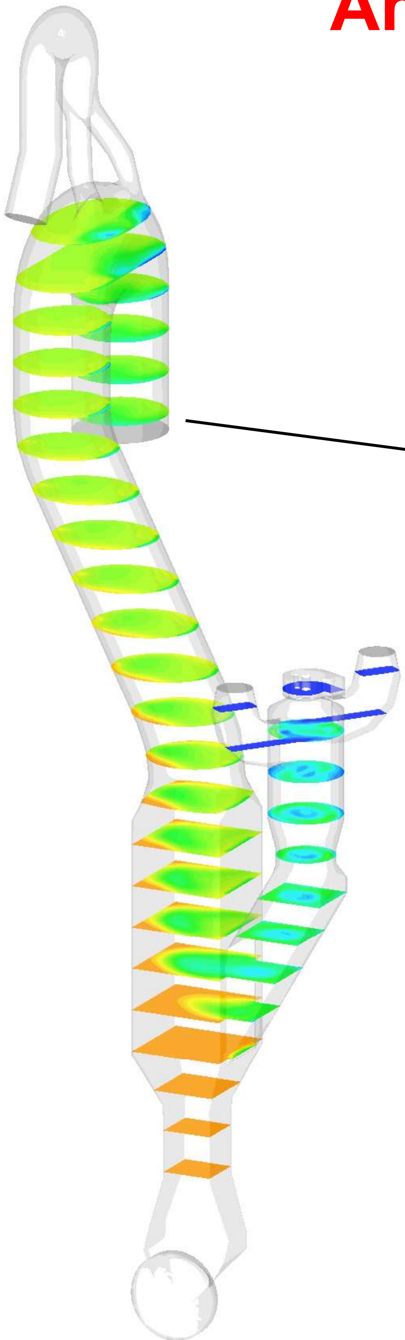
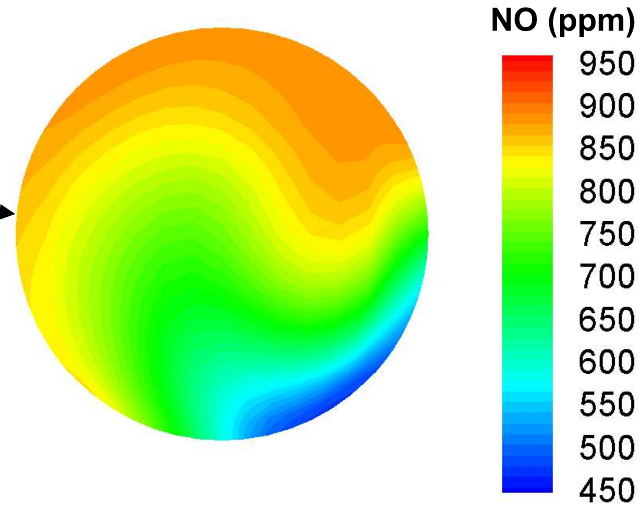
Analysis of Base Case Results – NOx



Average Value:
770ppm

Exit range NOx :
500-900 ppm



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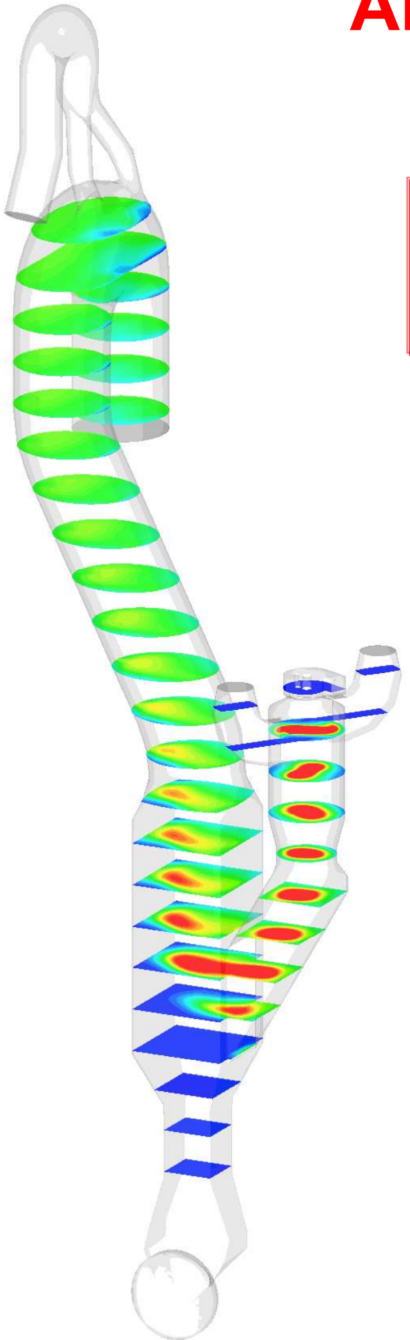
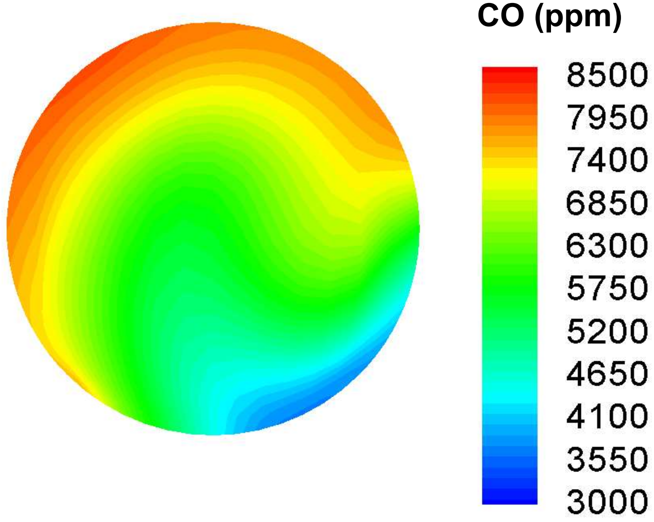
Analysis of Base Case Results – CO



Average Value:
6048ppm

Exit range CO :
3000-8500 ppm



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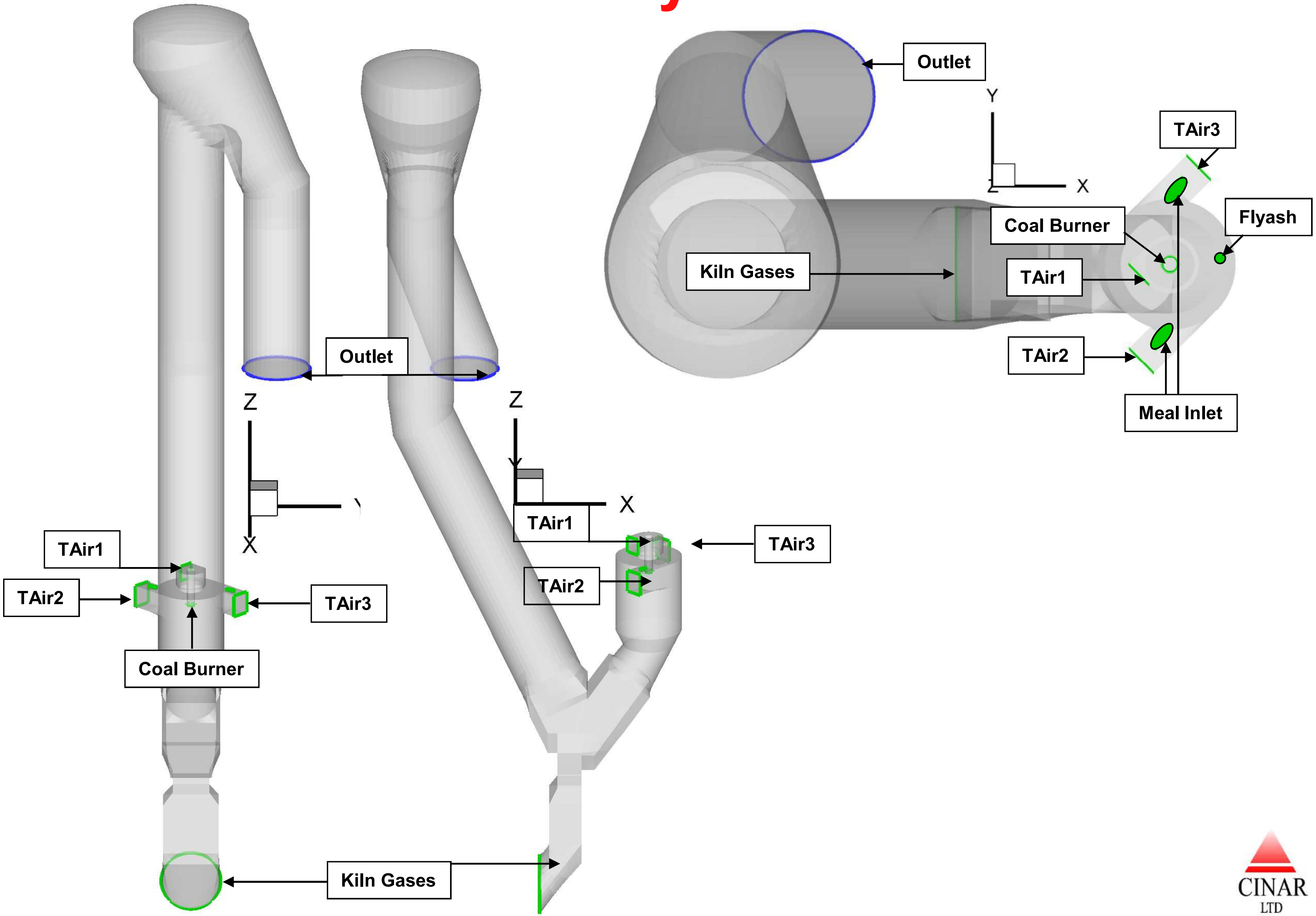
Another example of RSP

RT: 5 seconds

Calciner Geometry and Dimensions



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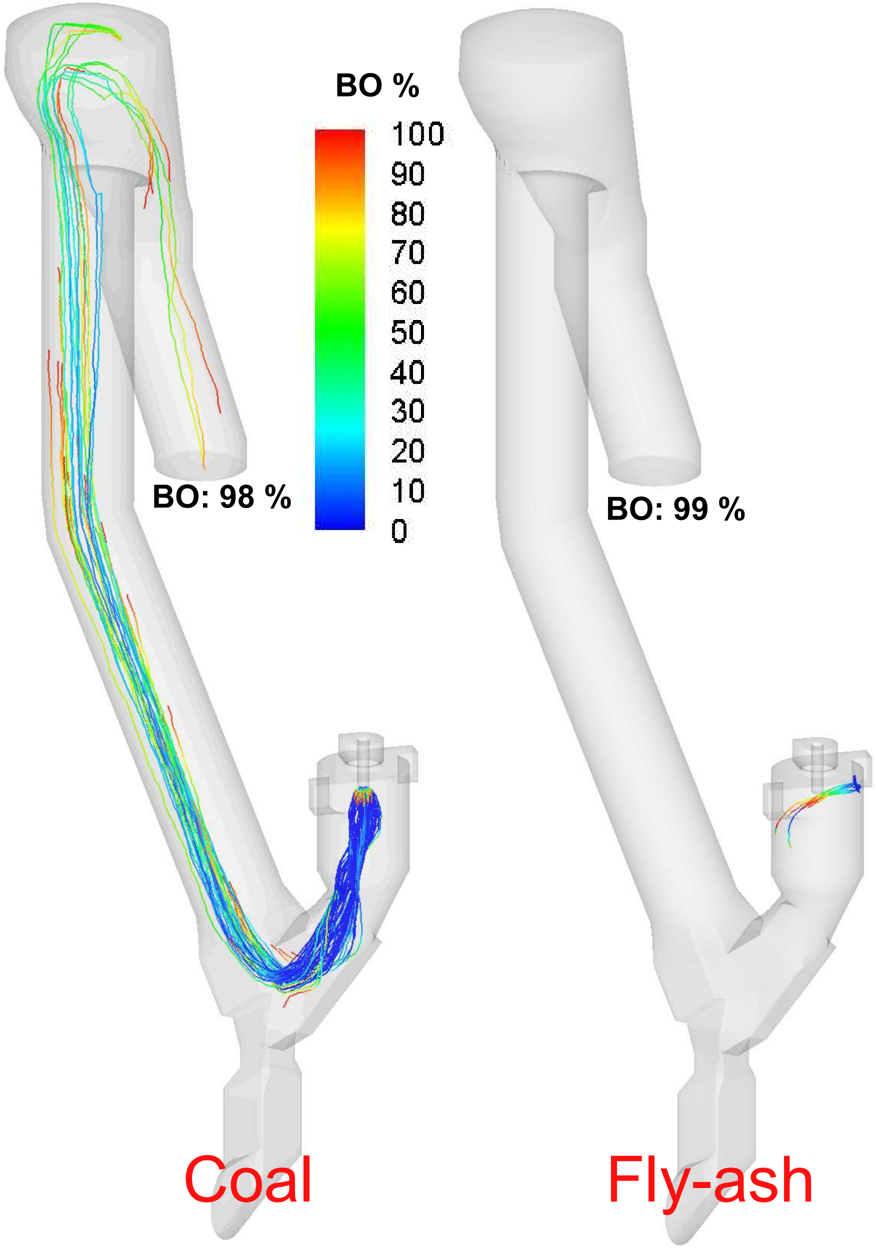
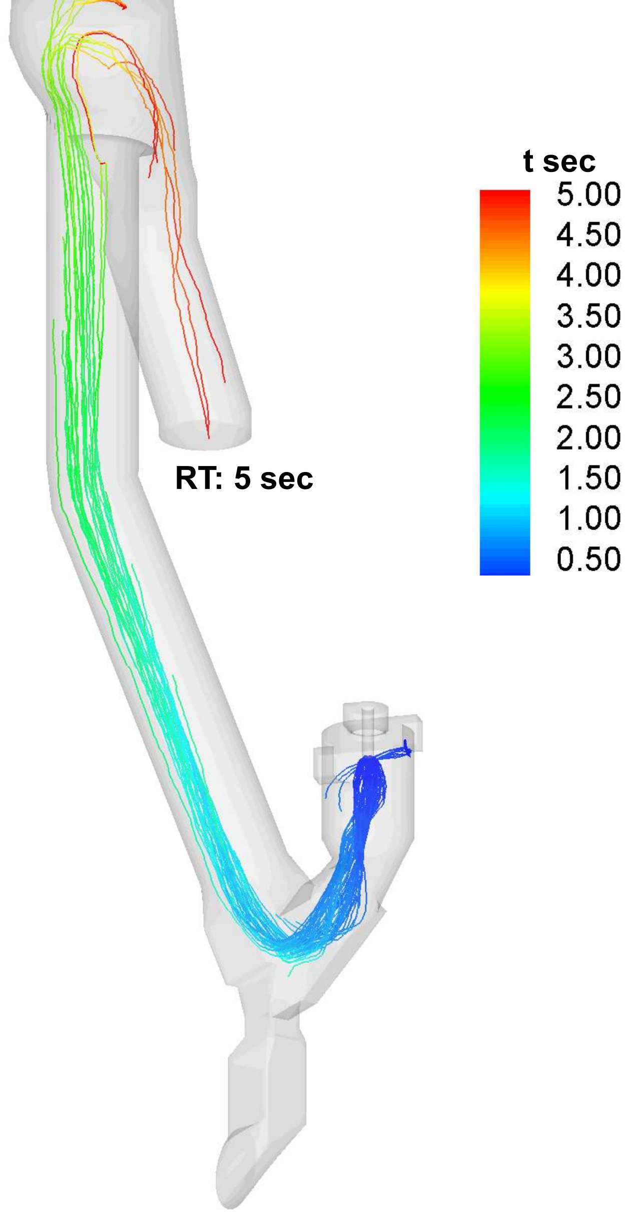
Analysis of Base Case Results

Burnout



Residence Time



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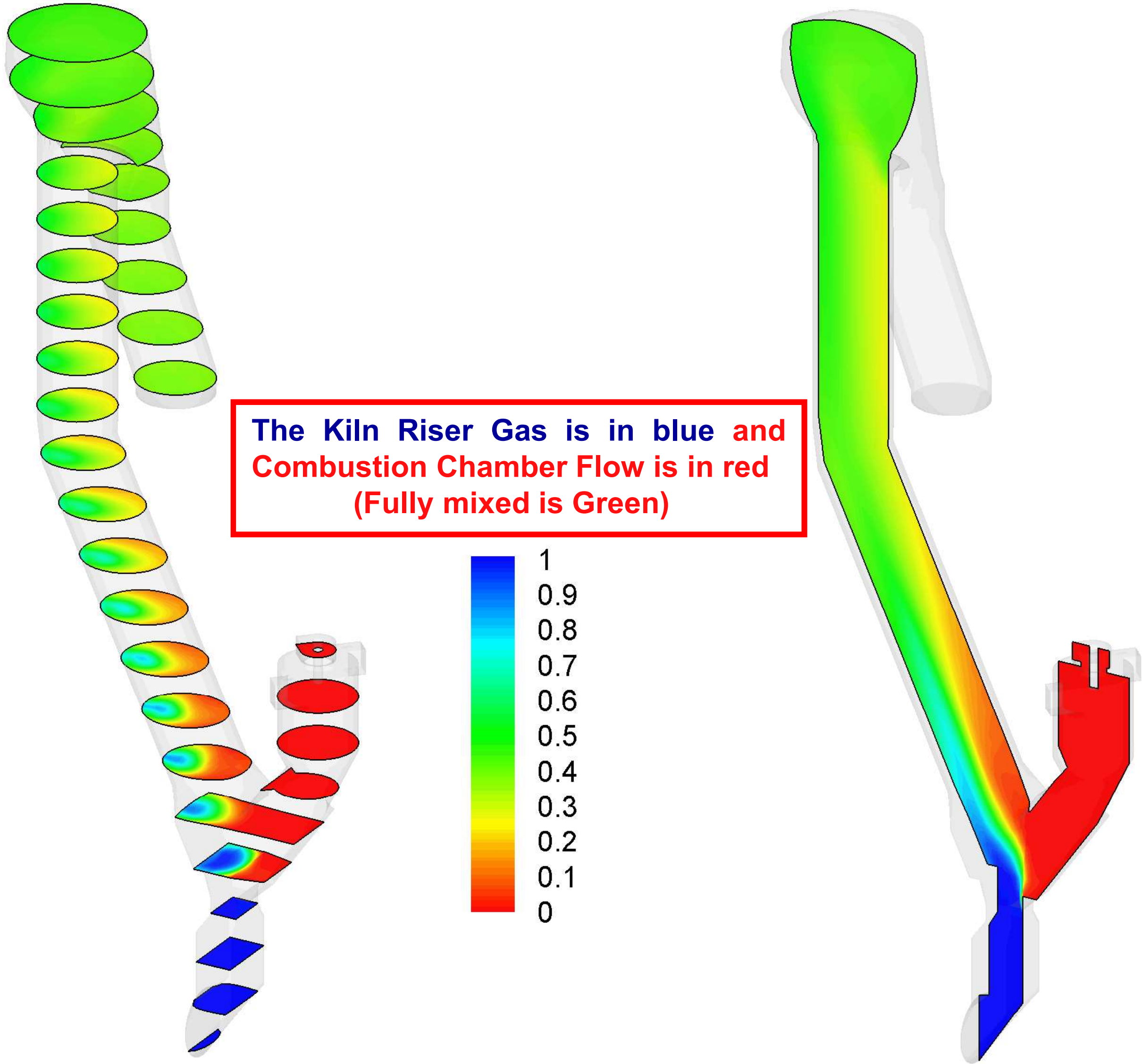
Analysis of Base Case Results – Mixing of KRG with Combustion Chamber Flow



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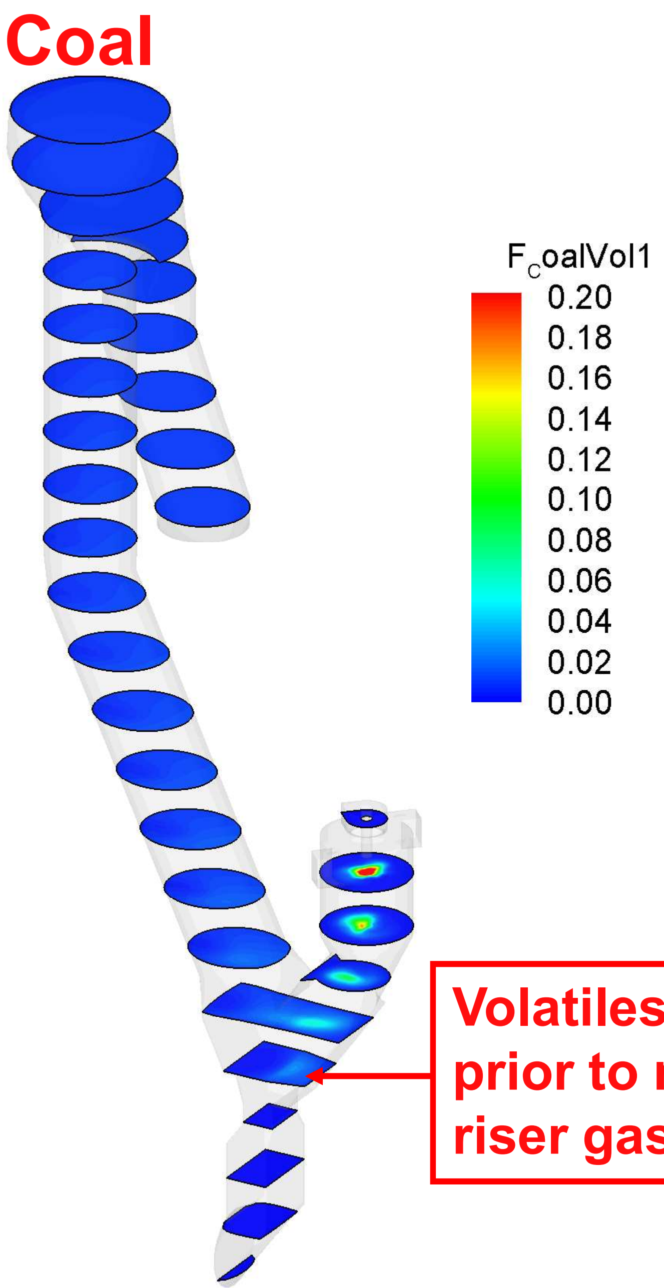
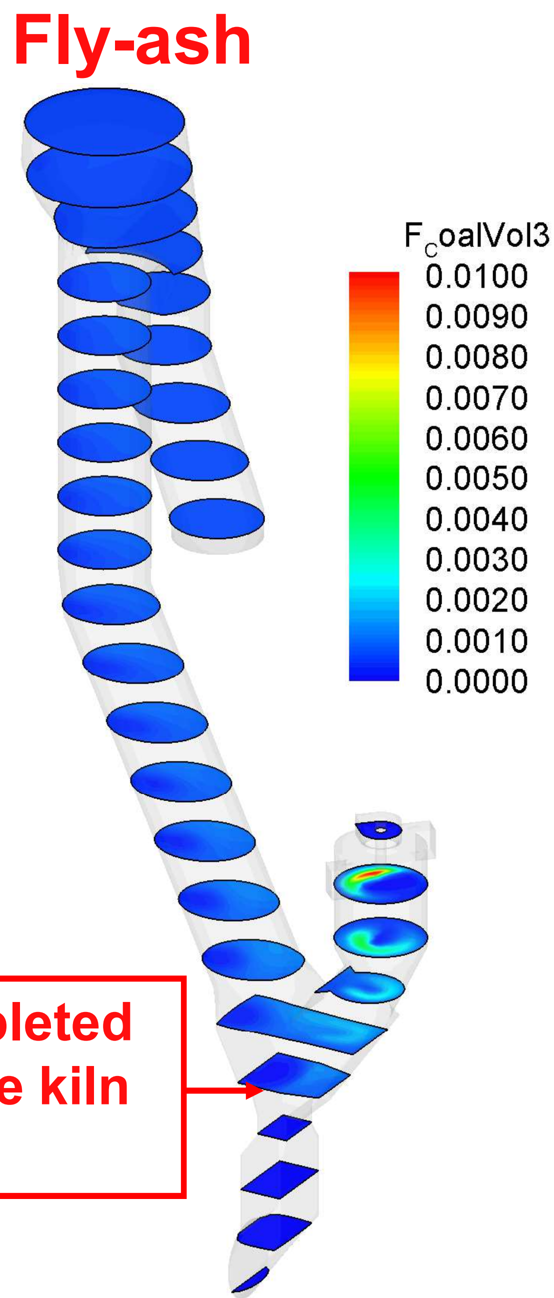
Base Case - Volatiles





Volatiles are almost depleted prior to meeting with the kiln riser gases

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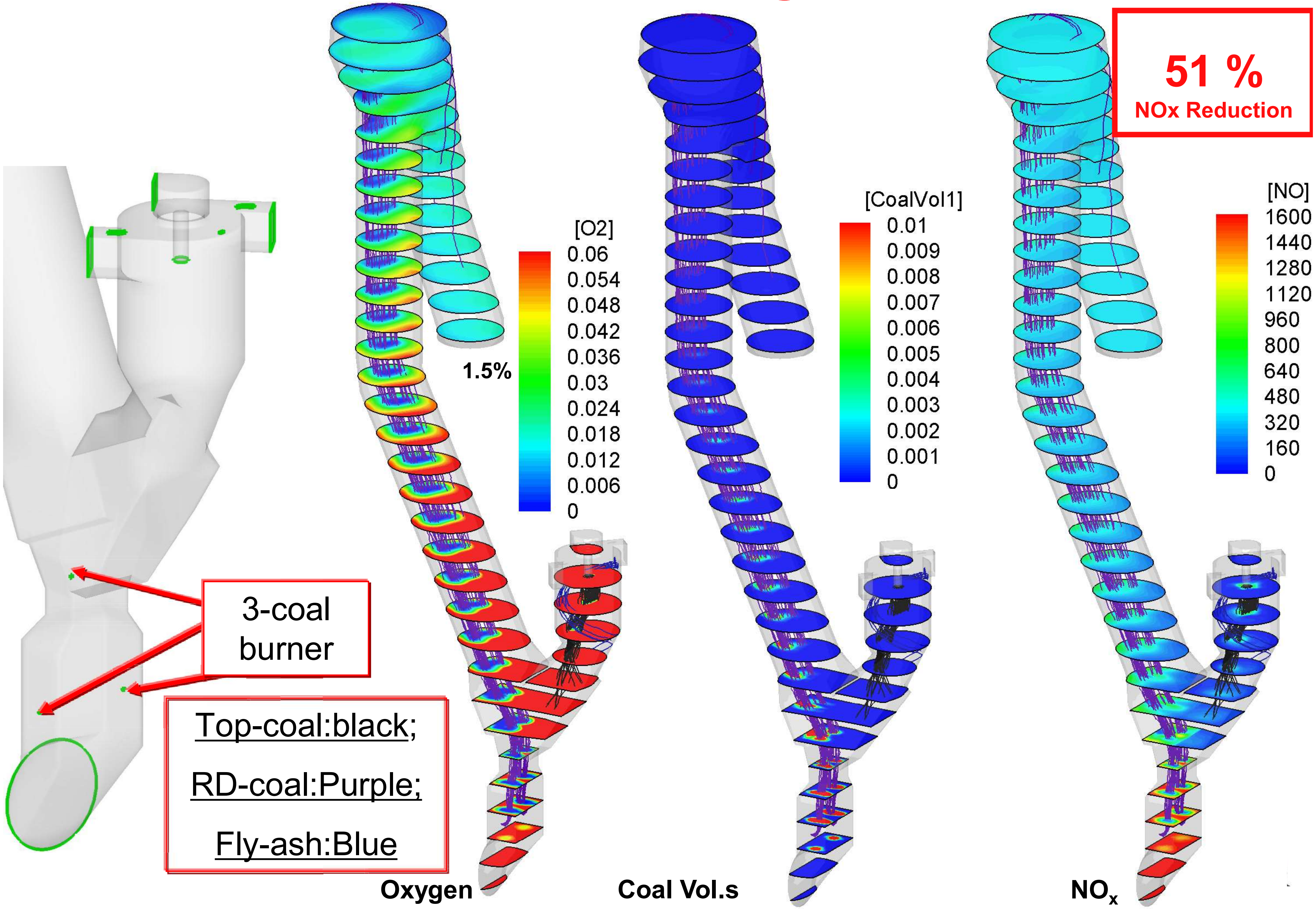
The Original Concept of Air staging was Modified to fuel staging (Reburn)!

51% NOx reduction via firing 80% of coal in RD



NOx reduction in In-line Calciners

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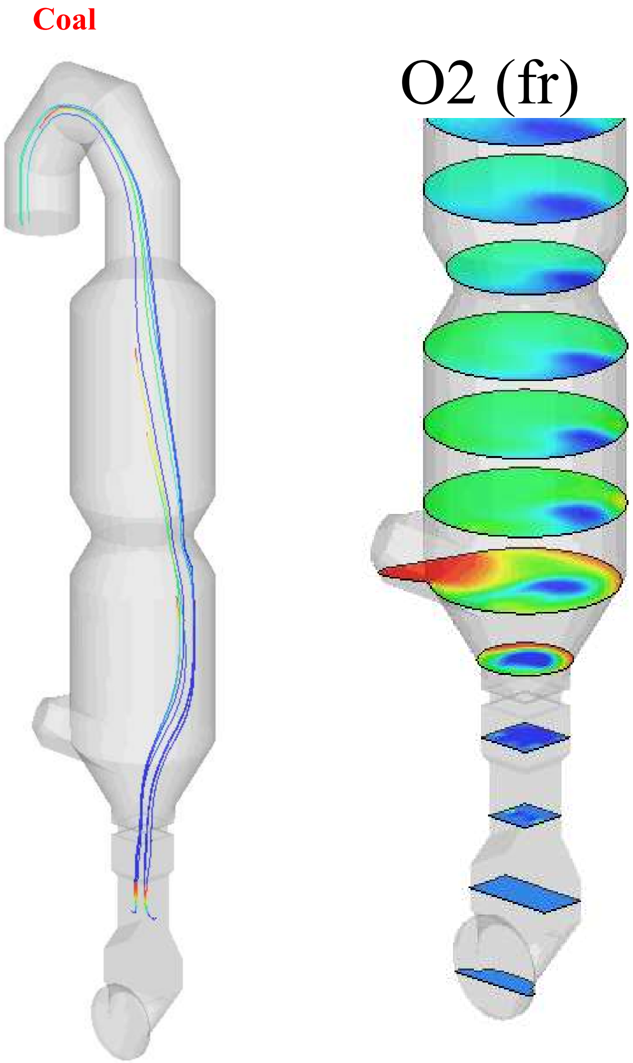
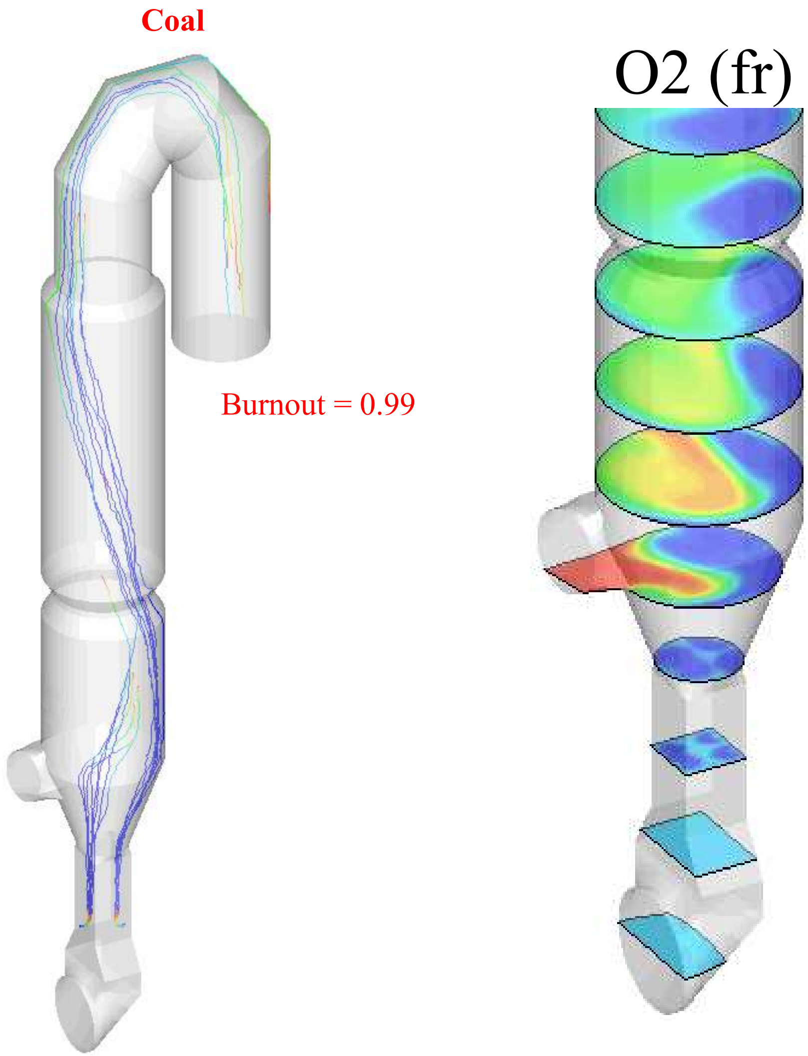
Geometry -I



Geometry -II



Reduction of both NOx and CO

Data: Geometry-I

CO: 830 ppmv

NOx: 848 ppmv

O2: 2.2%

Burnout: 99%

Data: Geometry -II

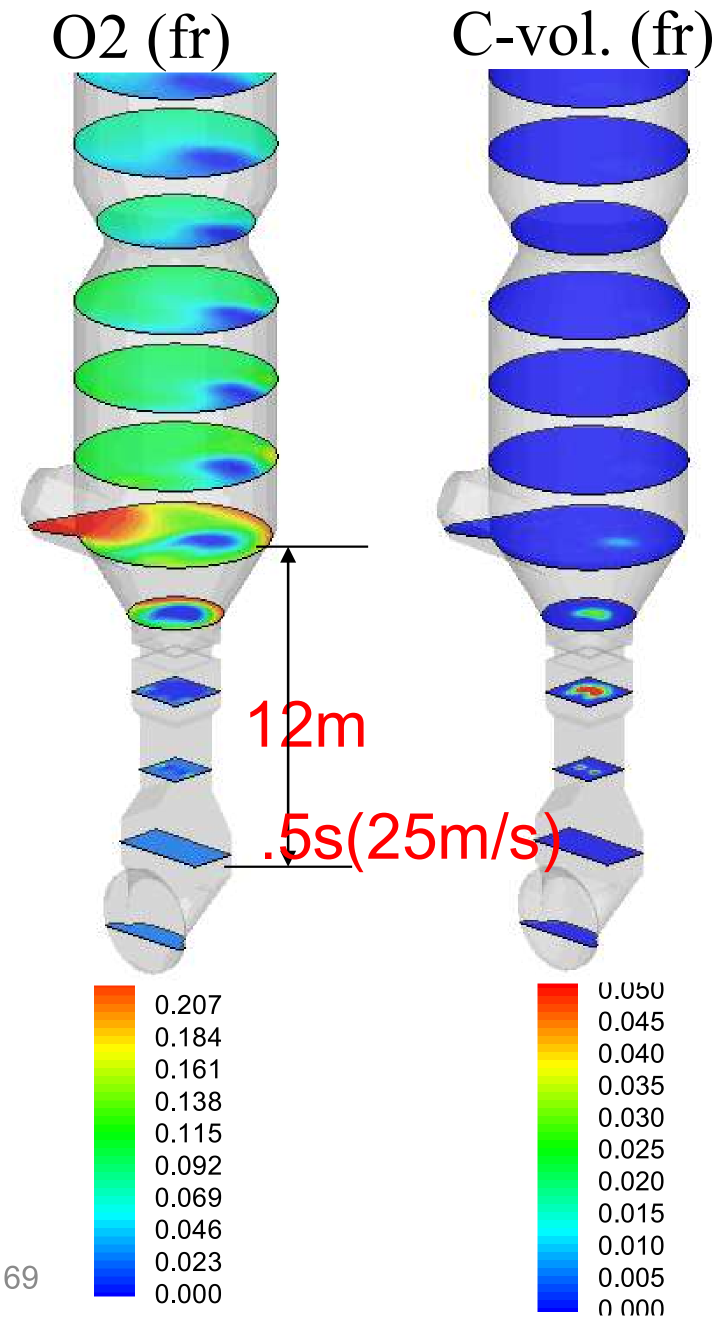
CO: 50 ppmv

NOx: 300 ppmv

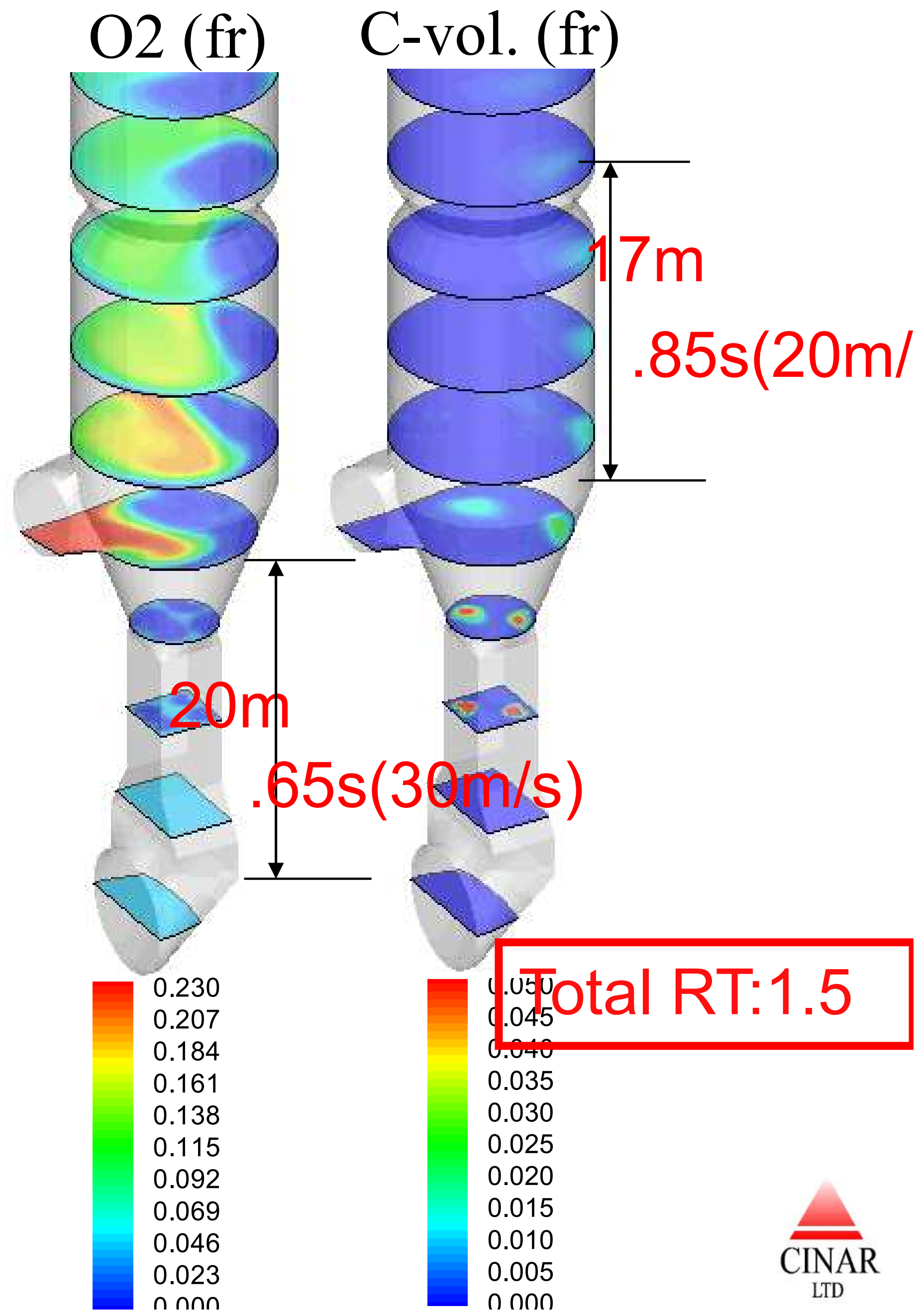
O2: 2.3%

Burnout: 99%

Geometry-I



Geometry-II



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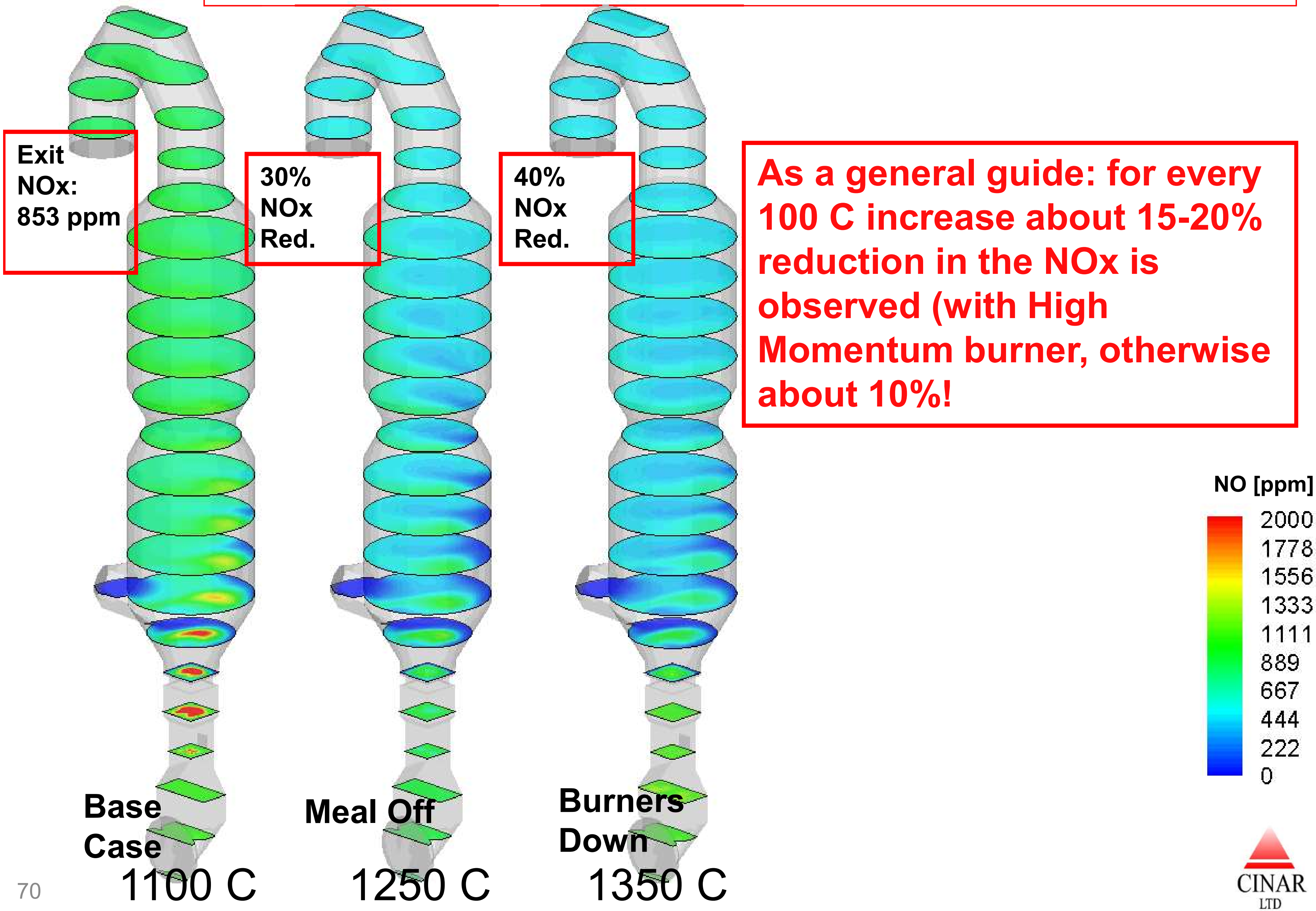
NO Concentration Profile: Geometry- I



As a general guide: for every 100 C increase about 15-20% reduction in the NOx is observed (with High Momentum burner, otherwise about 10%!

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Reducing NO/CO In Calciners

- Kiln generated NOx can be reduced from 50-85% in a calciner, depending on calciner configuration as well as several non-linear parameters;

- The conditions which are more favourable to reducing NOx/CO in a calciner are those which promote the destruction of NO via CHi and CO via OH radicals (reburn);

General Comments:

- Temperatures of up to 1200C, kiln backend oxygen of 3-6% with a good mixing of 'reburn fuel volatiles' over a residence time of about 0.5 second, followed by the gradual TA/JAMS mixing over a residence time of about 1.5 second are found to be the most important parameters, among others, i.e., volatile content, fuel nitrogen content, kiln NOx, burner momentum.

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Anything Missing on the NOx Issues!

- Well, its complex, there are some natural gas-fired calciner producing high NOx (we have not studied those yet!)

- We are studying two calciners these days with high NOx issues, a separate line calciner, and an line calciner, where even the SNCR does not work! (Max.10% NOx reductions)

- But, like before, a plausible solution will be found and concepts will be shared in the 4th one!

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Reducing NOx Beyond Combustion Modifications

(Reburn plus SNCR)

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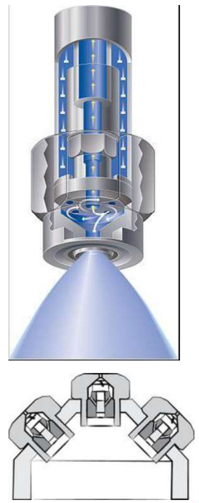
SNCR (Selective Non-Catalytic Reduction)

A post-combustion technology ‘End of Pipe’.

Reduction of NO via NH_3 or NH_2CONH_2 (Urea) takes place at a ‘narrow’ temperature Window :

- For NH_3-(870-980 C)
- For Urea (980-1150 C)
- Spray patterns and dispersion rates;
- Retractable multiple port lances (with cooling jackets) are used to mix reagent with calciner gases;



$$NH_2CONH_2 \rightarrow 2NH_3 + CO_2$$

$$NO + 4\ NH_3 \rightarrow 4\ N_2 + 6\ H_2O$$

SCR: Even more expensive!

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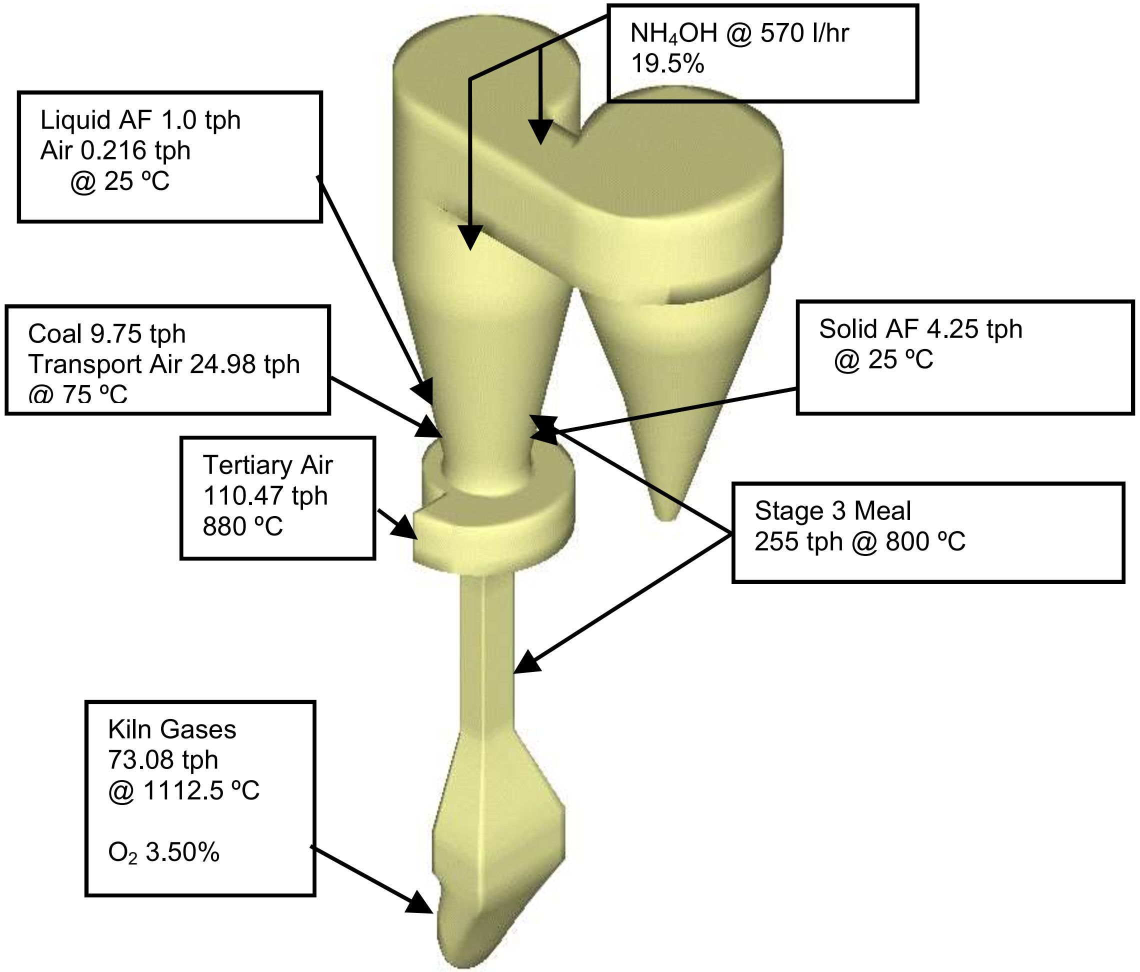
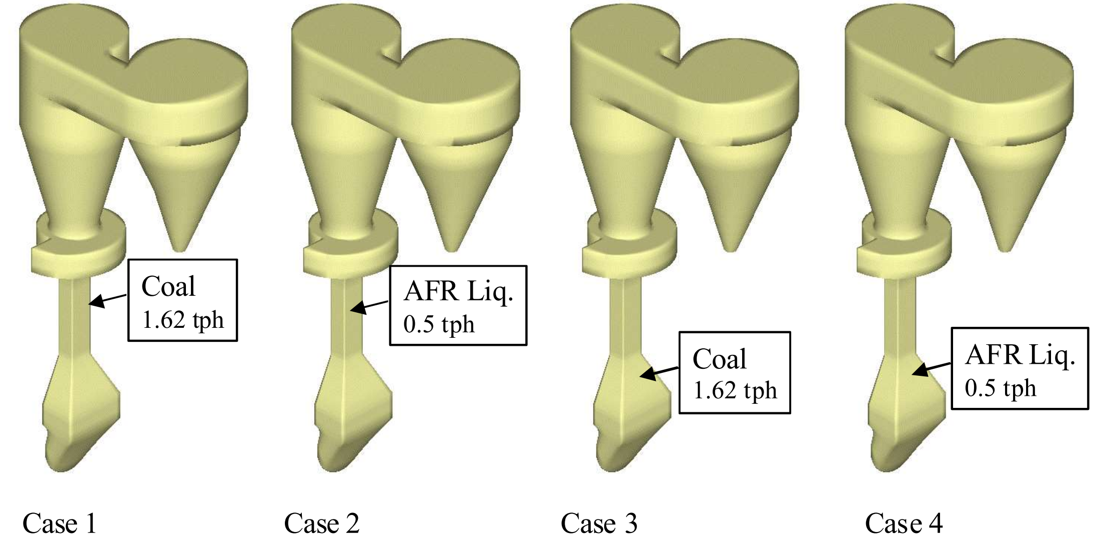
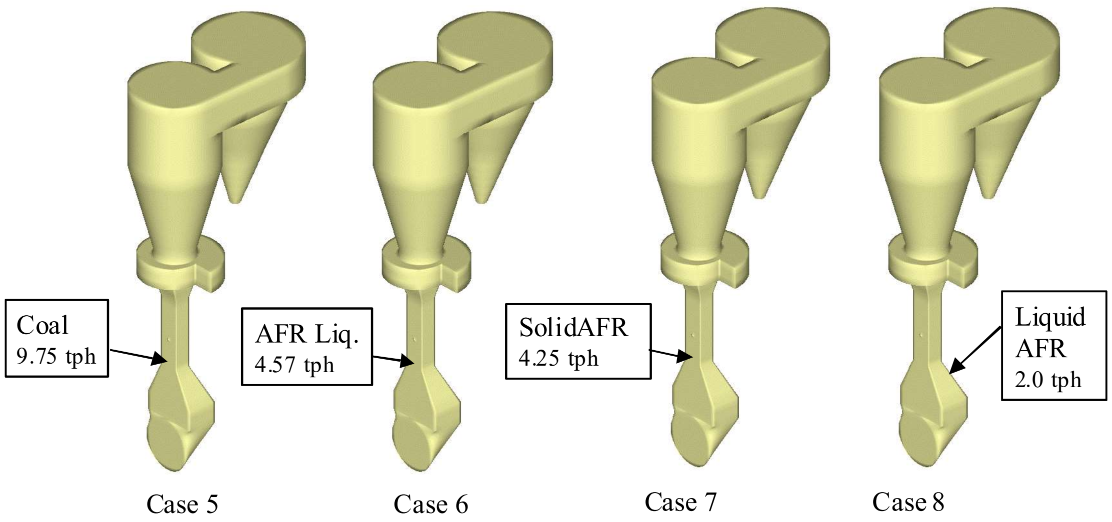
SNCR In-Line Precalciner: RT=1.5 s



NOx Reduction In-Line Precalciner





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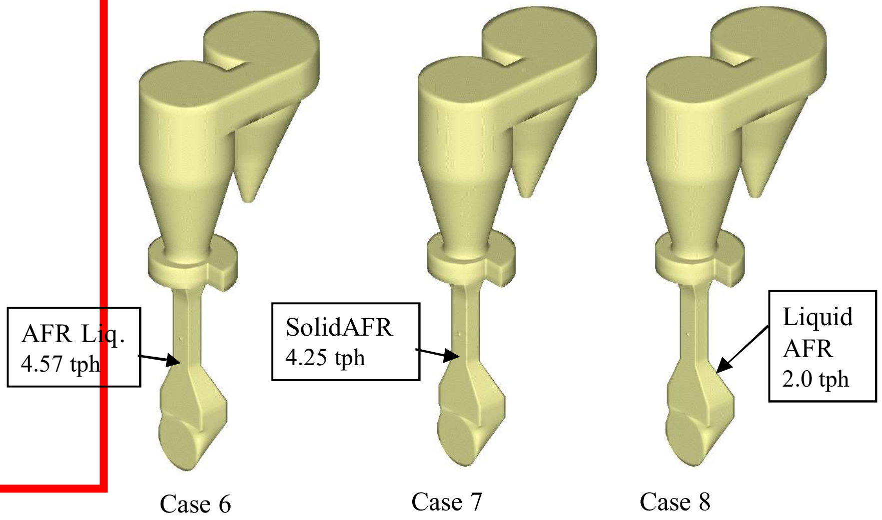
Reburn Optimisation

Cases	Fuels			NO[ppm]
[tph]	Coal	AFR(S)	AFR(L)	
B Case	9.75	4.25	1.00	652
Case 1	9.75	4.25	1.00	648
Case 2	9.75	4.25	1.00	651
Case 3	9.75	4.25	1.00	607
Case 4	9.75	4.25	1.00	649
Case 5	9.75	4.25	1.00	604
Case 6	5.00	4.25	4.57	393
Case 7	6.22	9.50	1.00	472
Case 8	8.40	4.25	2.00	581

Max. NOx reduction: 40%



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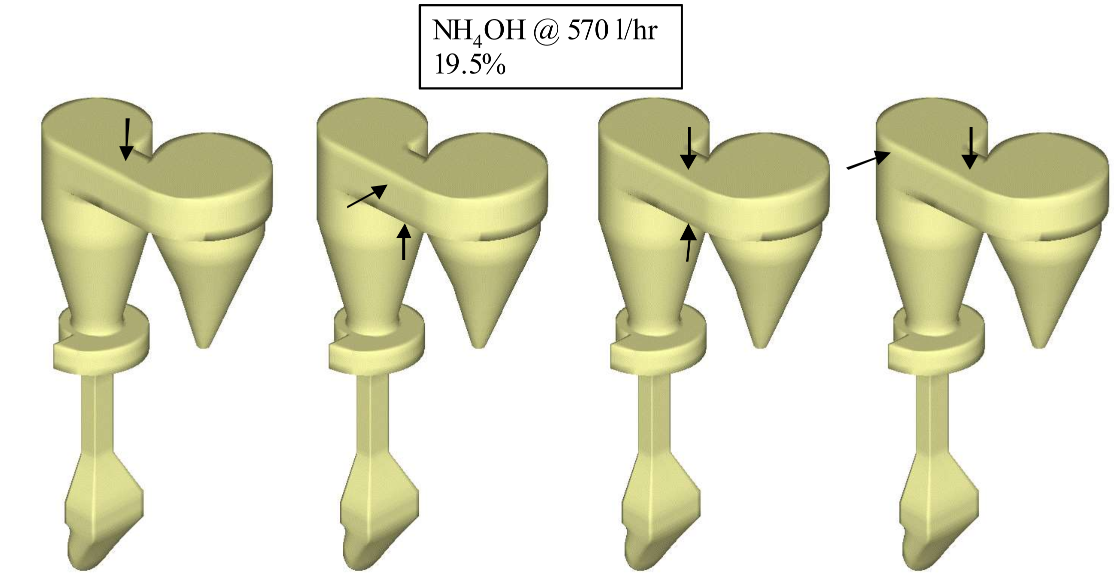
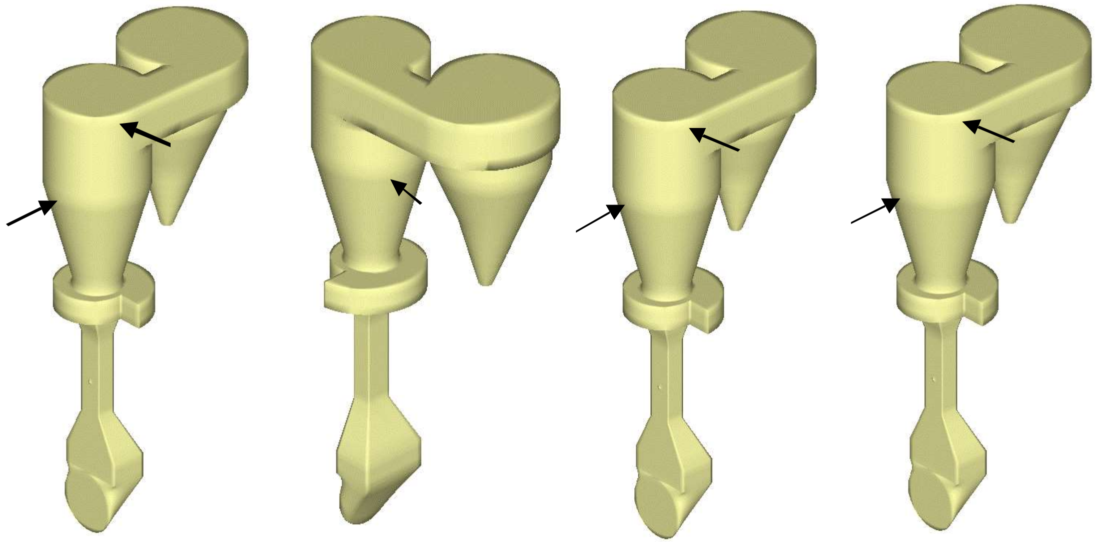


SNCR Case 2 | SNCR Case 3 | SNCR Case 4 | SNCR Case 5



SNCR Case 6 | SNCR Case 7 | SNCR Case 8 | SNCR Case 9

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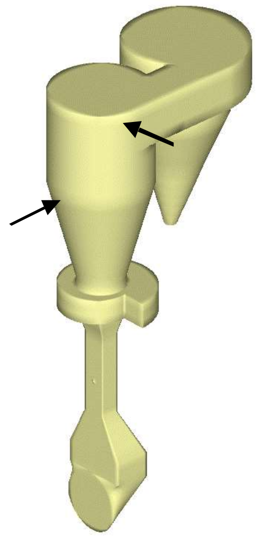
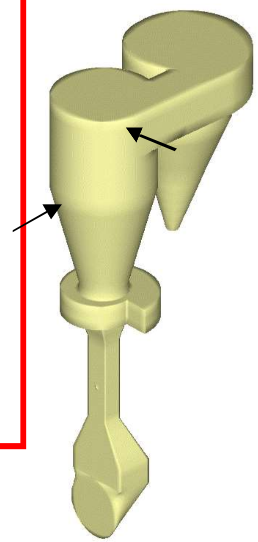
SNCR plus Reburn Optimisation

Cases	Fuels (tph) Coal	AFR (S)	AFR (L)	NO (ppmv)	NH3] (ppmv)
SNCR Case 1	9.75	4.25	1.00	350	212
SNCR Case 2	9.75	4.25	1.00	404	132
SNCR Case 3	9.75	4.25	1.00	367	103
SNCR Case 4	9.75	4.25	1.00	334	169
SNCR Case 5	9.75	4.25	1.00	338	218
SNCR Case 6	9.75	4.25	1.00	320	118
SNCR Case 7	9.75	4.25	1.00	574	14
SNCR Case 8	5.00	4.25	4.57	223	152
SNCR Case 9	6.22	9.50	1.00	224	81

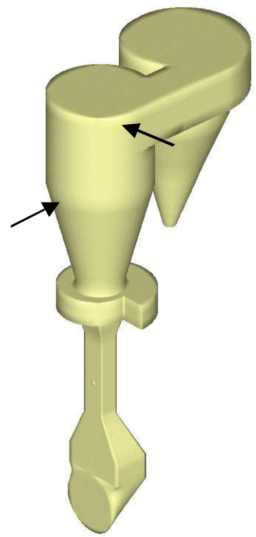
Max. NOx reduction: 12%



SNCR Case 6



SNCR Case 8



SNCR Case 9

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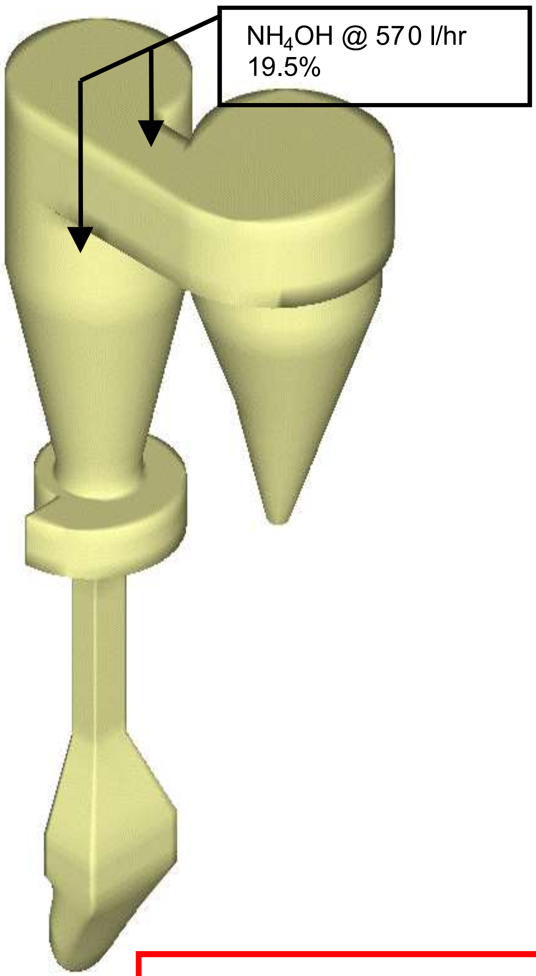
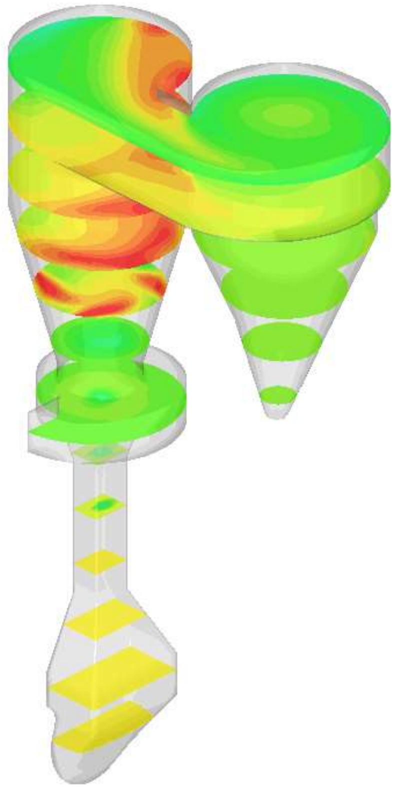
Temperature [ºC]





SNCR (Exit Temperature 860 ºC)

Flow and temperature stratification plus not enough residence time!

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SNCR/SCR

- SNCR is well established in the boiler sector and on some Plants can get down to 200 mg/NM3
- However both CO and NH3 compete for OH radicals and a higher concentration of CO temperature window also shifts by 50-100 C, due to several reasons:
  - Temperatue and flow is stratified;
  - Insufficient mixing (injectors) + need 1-1.5 s residence time
- A plant which operates at 200 mg/Nm3 has 16 injectors and it took them 2 years to get there
- With MI-CFD it can be much quicker!!

- SCR, at much lower temperatures (300-450 C), NH3 to NO molar ratio 1:1 in the presence of catalyst, for typically 80-90 % NOx reduction efficiency. Can be installed after PM control devices, Solnhofer, Germany

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