14th International Seminar on Furnace Design

Operation and Process Simulation

PRIME Glass Project: integrated experimental approach for the validation of numerical simulations

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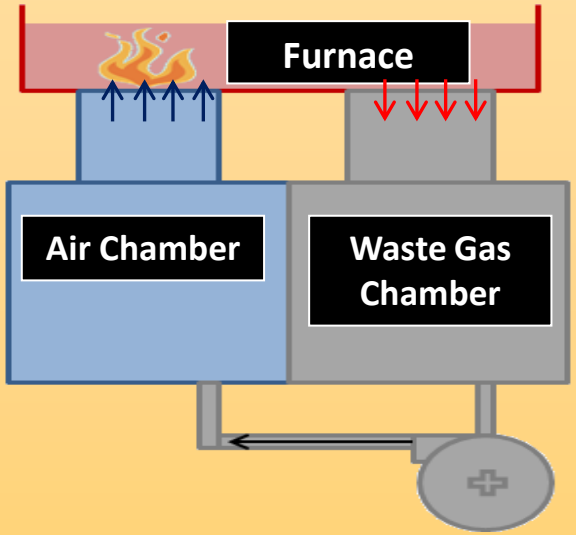
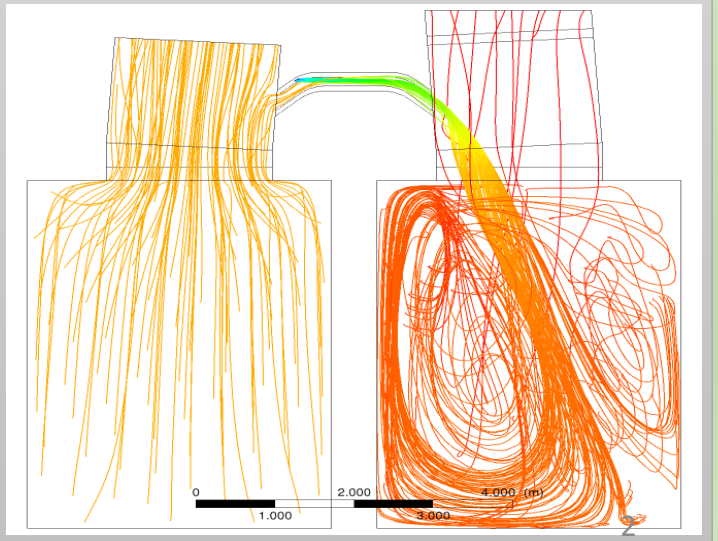
1. ***Strategic waste gases recirculation***: with this Primary NOx reduction technique a fraction of flue gases is drawn from the bottom of the regenerator chamber and injected into cold combustion air (at the bottom of the other chamber) by means of a high temperature resistant fan and of a purposely designed ducting system. Bearing less O_2 and more radiating species (H_2O, CO_2), injected flue gases reduce NOx generation and enhance heat exchange in the regenerator.

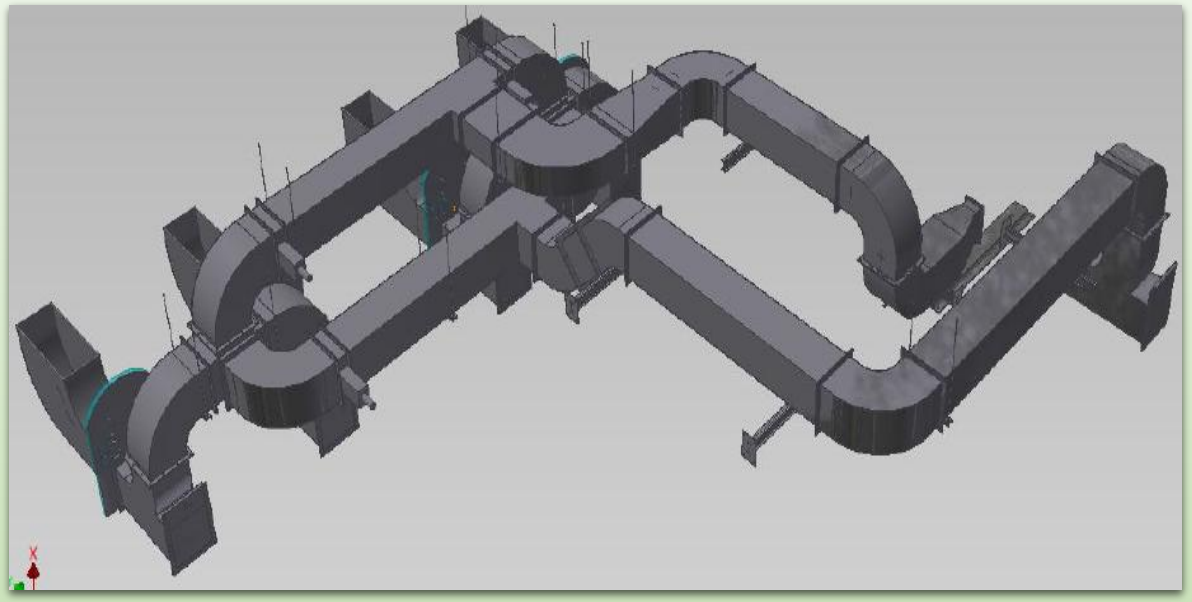


2. ***Enhanced hot air staging***: also called **hybrid air staging**, this technique reduces the production of thermal NOx by lowering excess combustion air inside the furnace and completing CO burnout at lower T inside the waste gases port neck, by means of high speed injection of preheated air, which is spilled from the other port and propelled by jets of compressed cold air (thus "*hybrid*"). This leads to less NOx formation while minimizing the energy losses with respect to a pure cold air staging.

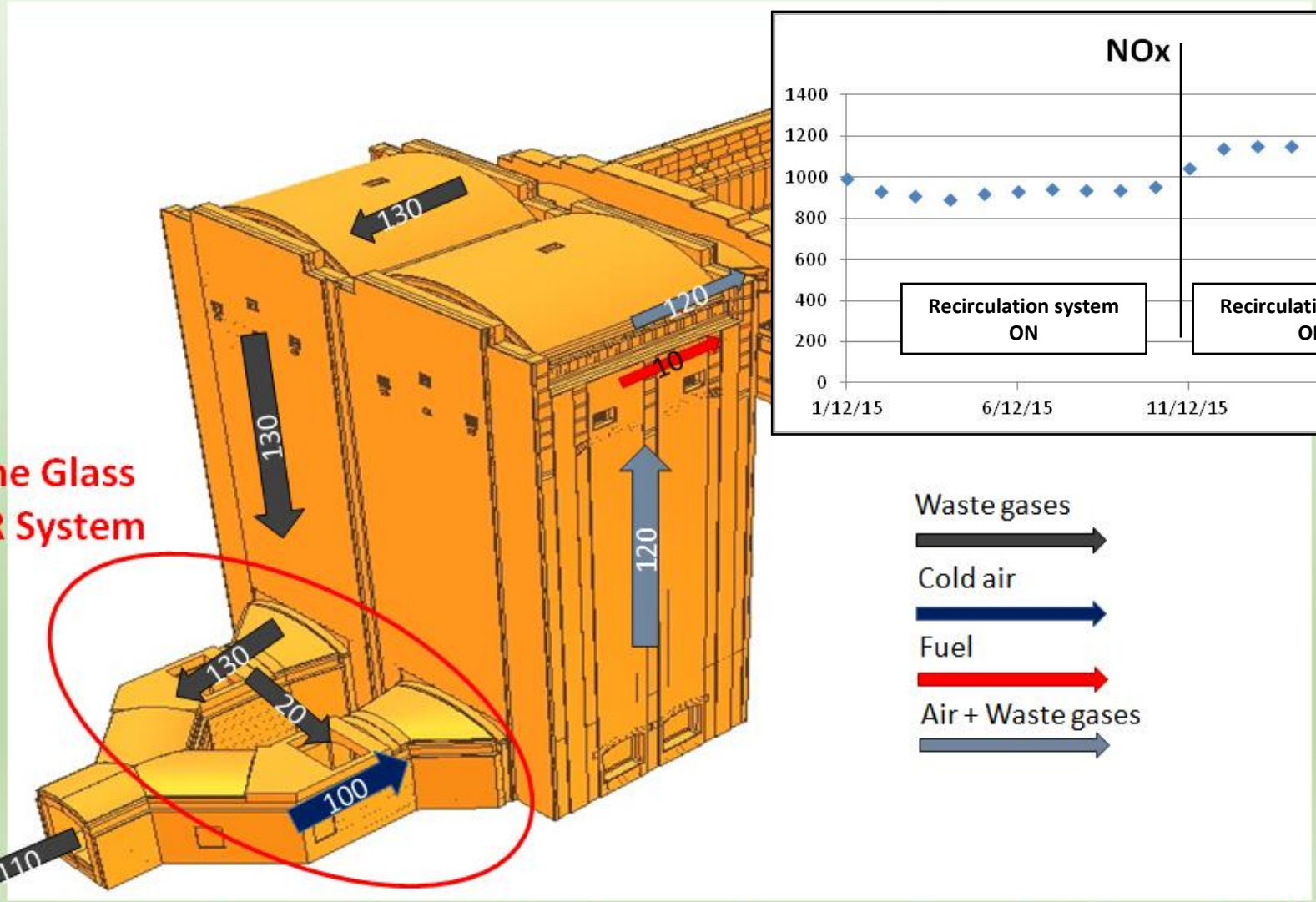


Strategic Waste Gases Recirculation (WGR)

Two full scale embodiments of a PRIME Glass Strategic Waste Gases Recirculation unit (WGR) have been installed at the bottom of the regenerators of the Bormioli Rocco / Vetropack **Trezzano** (Italy) **Furnace F3** and of the Vetri Speciali **S.Vito al Tagliamento** (Italy) **Furnace F2**.



End Port furnace 15% Waste Gases Recircualtion

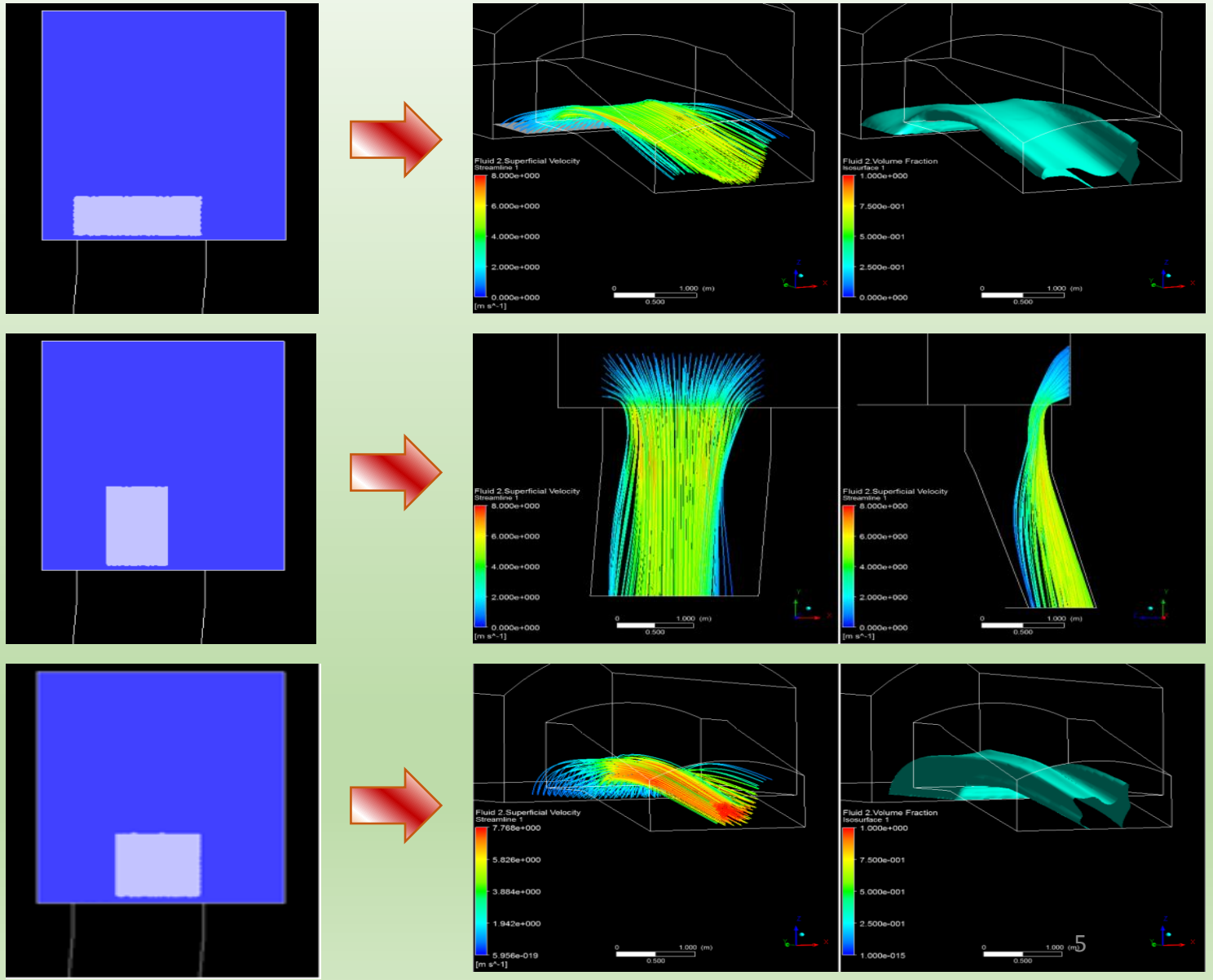


The reported percentage numbers are referred to total air flow rate and represent only an explanatory example of WGR settings

WGR system DESIGN

First of all, studies were performed to determine the **most effective waste gases distribution pattern** **in the port** for the minimization of NOx generation by the flame. Such configuration would be the target to aim at in designing the geometry of the flue gases injection system.

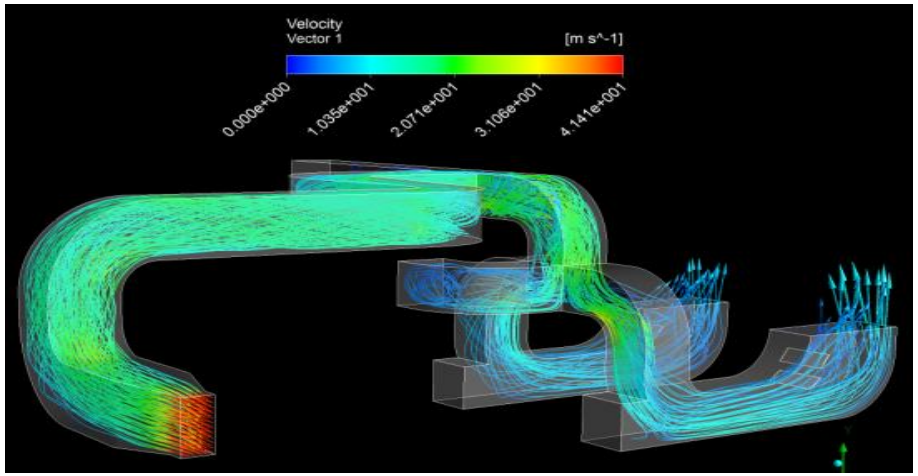
The most desirable pattern was found to be a **flat stratification of waste gases at the bottom of the port,** shielding the first part of the natural gas vein from O_2-rich preheated air, and delaying its mixing with fuel towards the tip of the flame. This would lower the T and hinder NO_x formation.

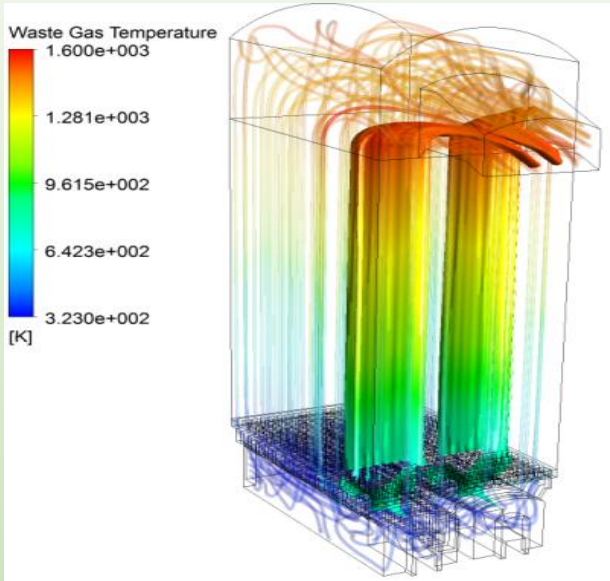


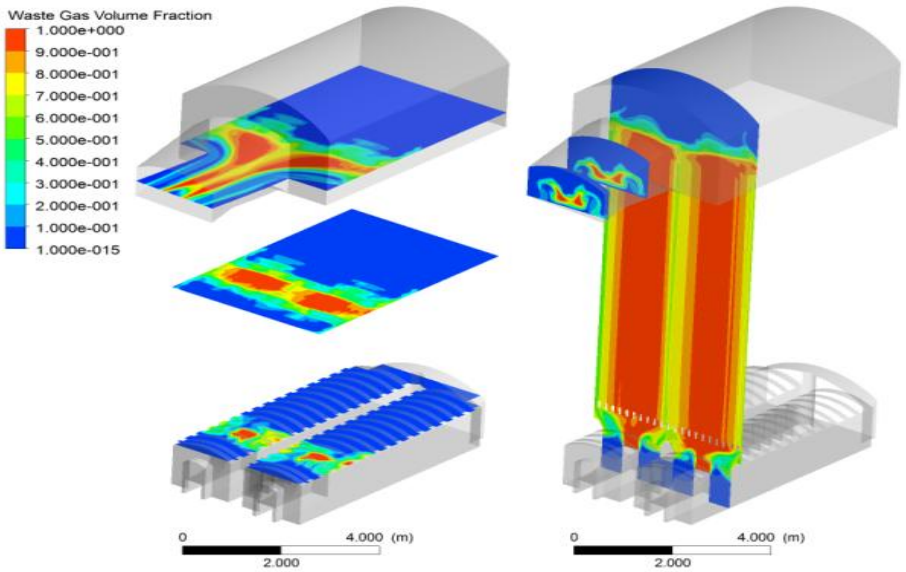
WGR system DESIGN

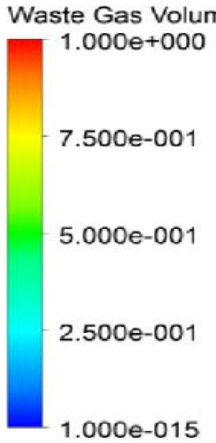
Detailed CFD studies were carried out on the regenerators, to **model the effects of the injection** of a stream of waste gases into combustion air from the bottom of the chamber.

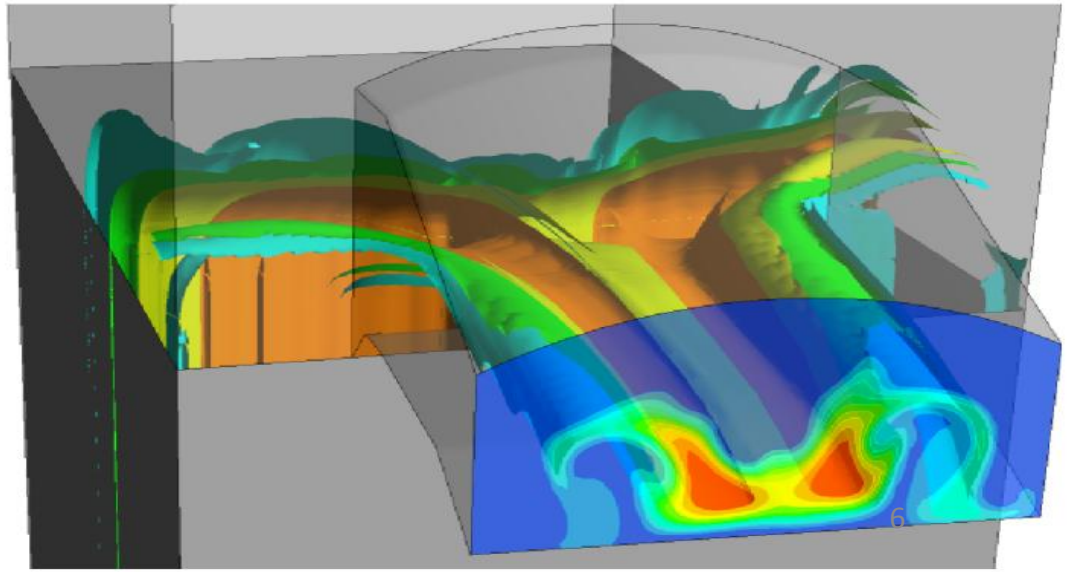
Then other CFD models were developed to simulate the actual system required for the recirculation of flue gases.







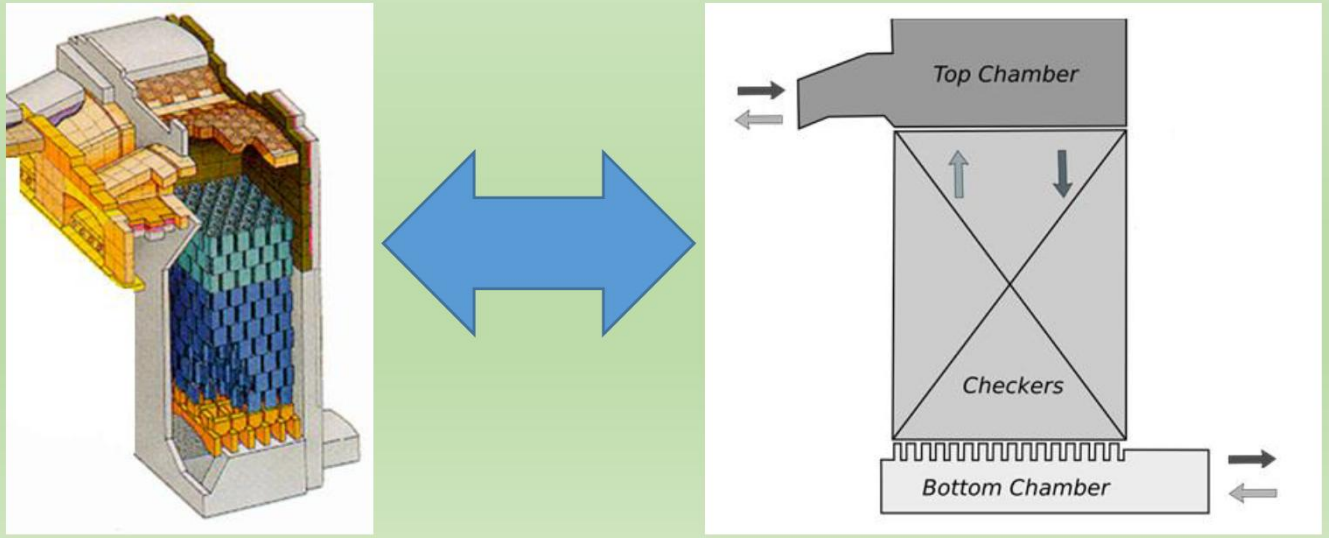




Regenerative chambers

The CFD modeling of the regeneration system is made in order to investigate the **thermal and fluid dynamic aspects** that occurs in the **cold and the hot regeneration phases.**
The regeneration chamber model moreover provides a support for the analysis of the furnaces subsystems such as the Strategic Waste Gas Recirculation and the Air Staging systems.

The computational domain is divided into three zones: top chamber, checkers zones and bottom chamber.
The thermo-fluid dynamic aspects in checkers zones are evaluated by means of a **Porous Domain** set-up by a transient analysis carried out on a **single flow channel**.

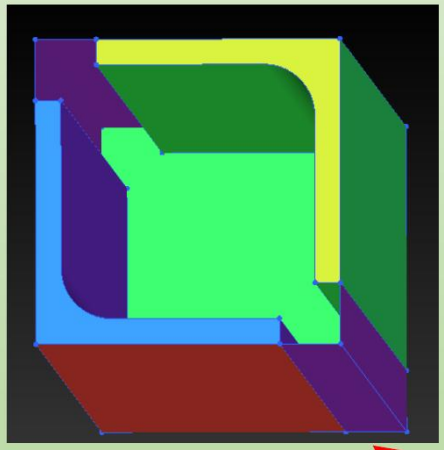


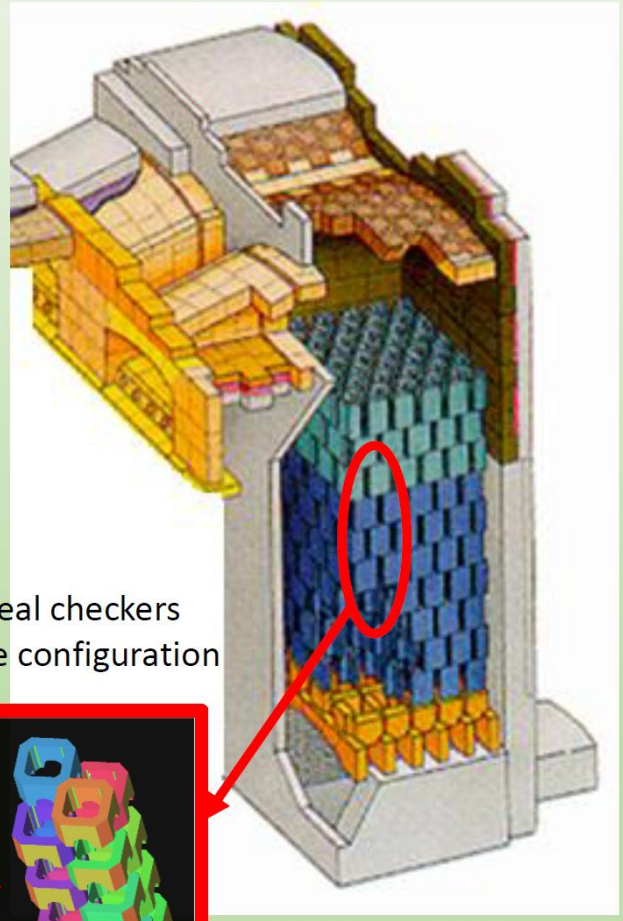
Single flow channel model

TWO POROUS MODELS:

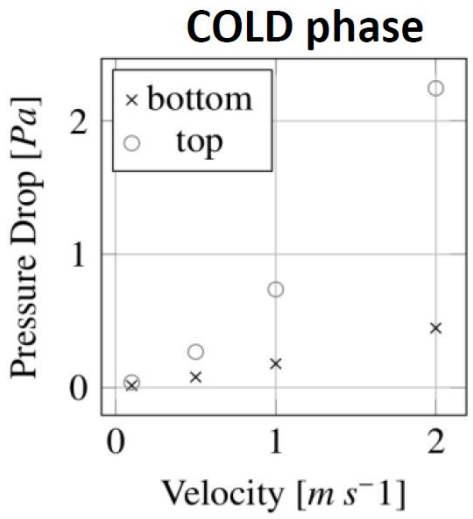
- **EQUILIBRIUM**
- **NON EQUILIBRIUM**

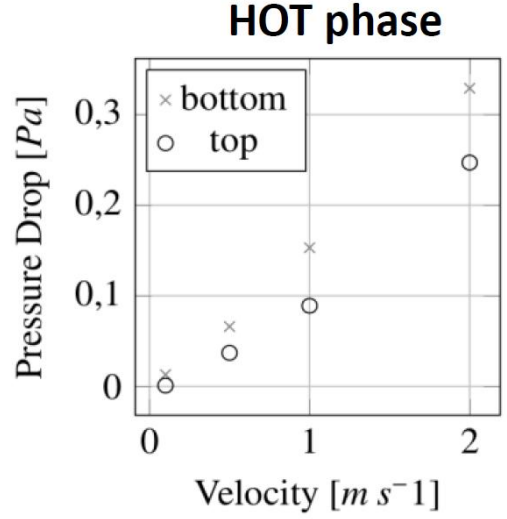
CFD Single flow channel cross section (5 m height)

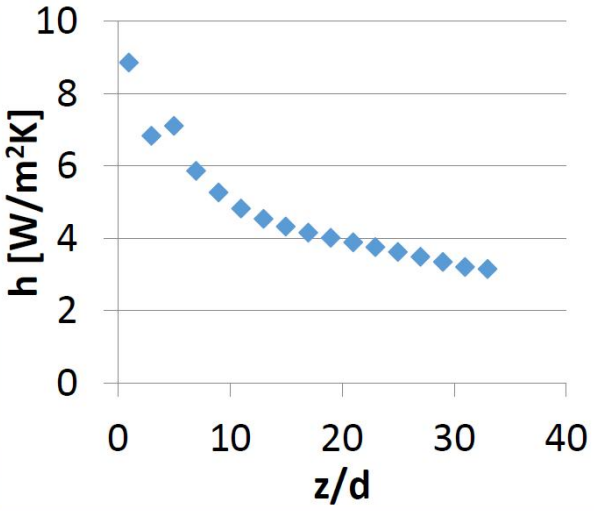


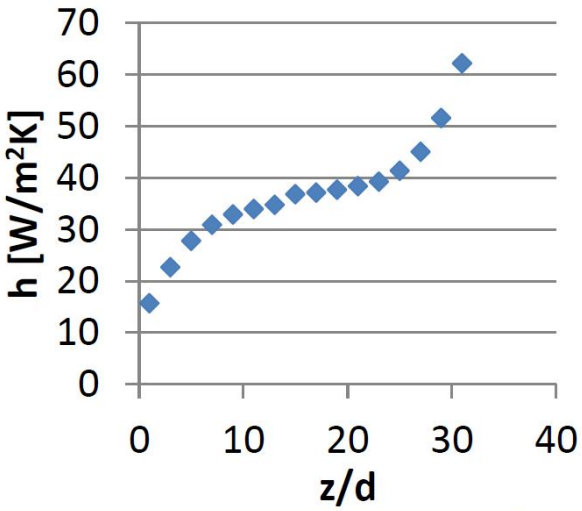


Real checkers zone configuration







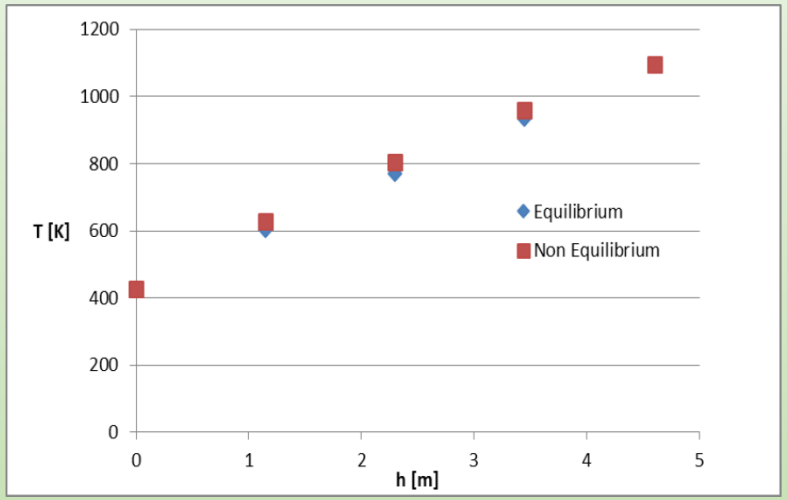


Porous models comparison

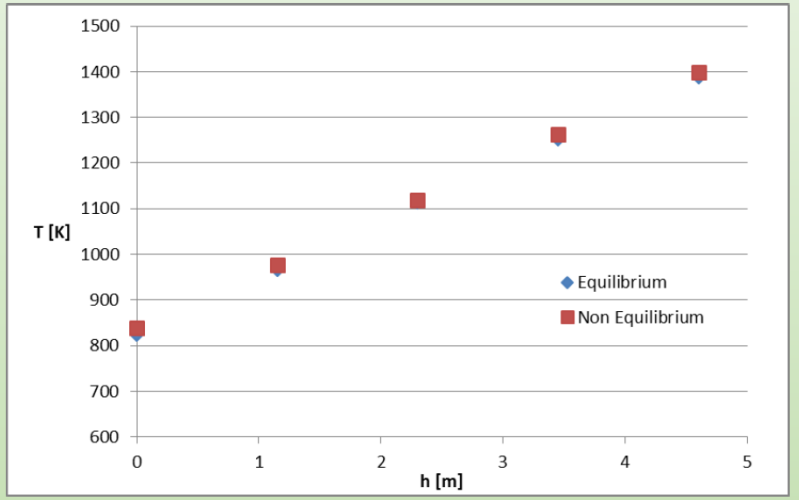
Temperature profile
across the checkers zone

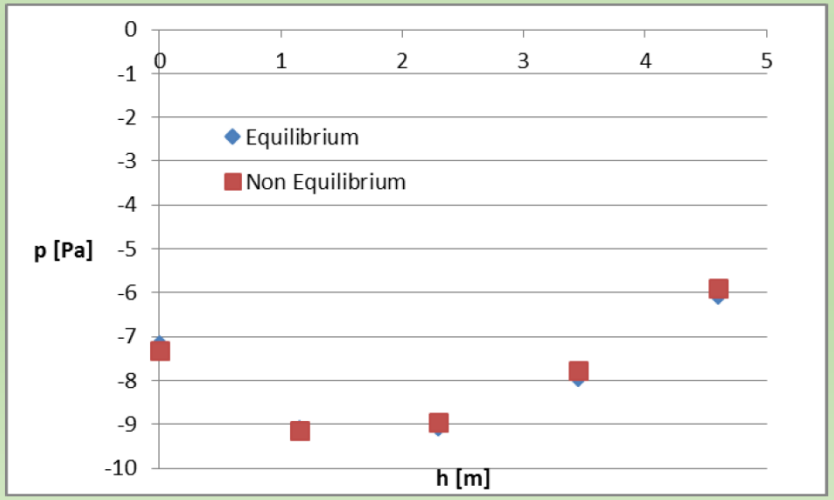
Pressure drop profile
across the checkers zone

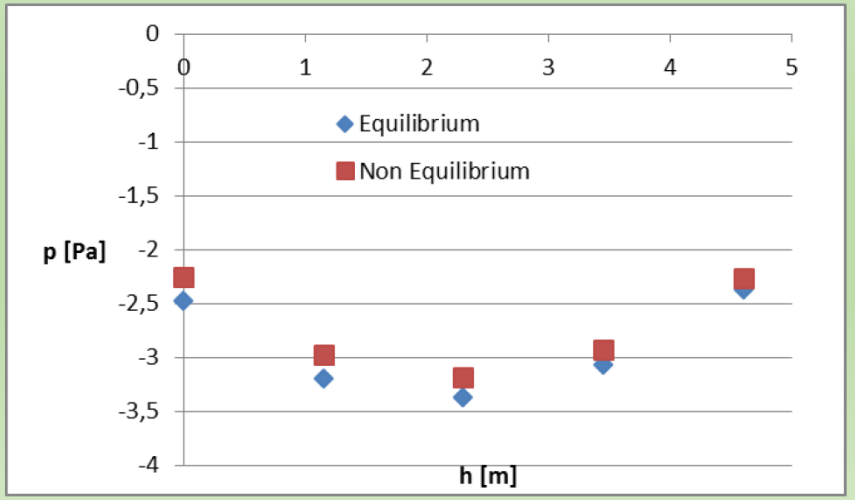
Air phase



Flue gas phase





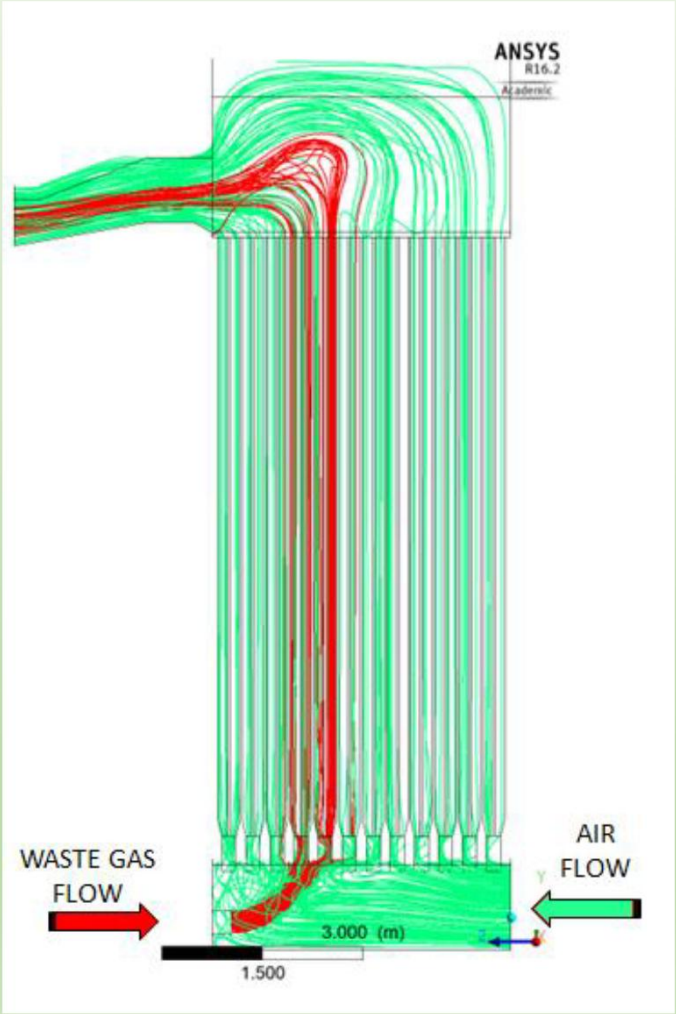


Strategic Waste Gas Recirculation system

The SWGR system is a technique for the removal of pollutants in new or existing glass furnaces.

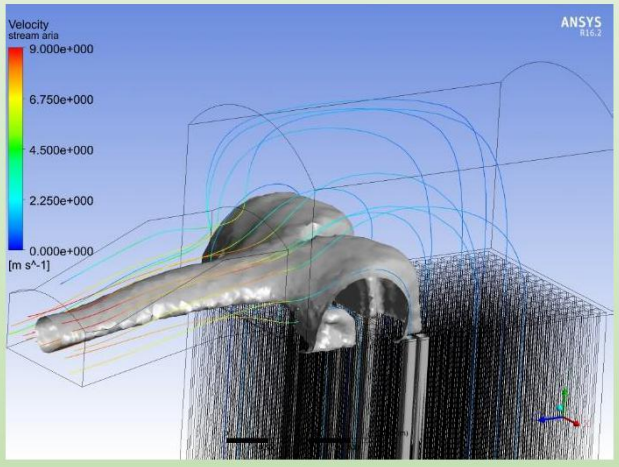
The system has a bypass of **flue gas** that is fed into the regenerator operating with air (cold phase). The flue gas is channeled into the stackers and then it is introduced in the combustion chamber.
To ensure a good performance of the system is fundamental that the flue gas flow remains **concentrated in the primary combustion zone** of the combustion chamber.
By means of the CFD analysis, the recirculation system can be **optimized and calibrated** to be coupled **to a given furnace geometry.**

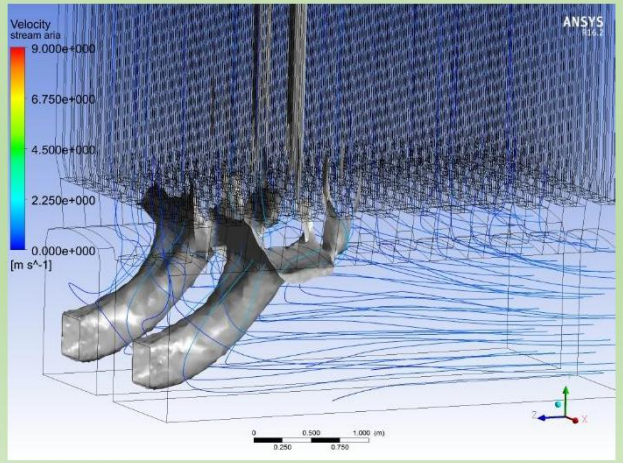
As demonstrated experimentally, the injection of waste gas has a **positive effect on the global heat exchange in the stackers**, the smoke-tracking enables to locate the areas where this phenomenon is concentrated.



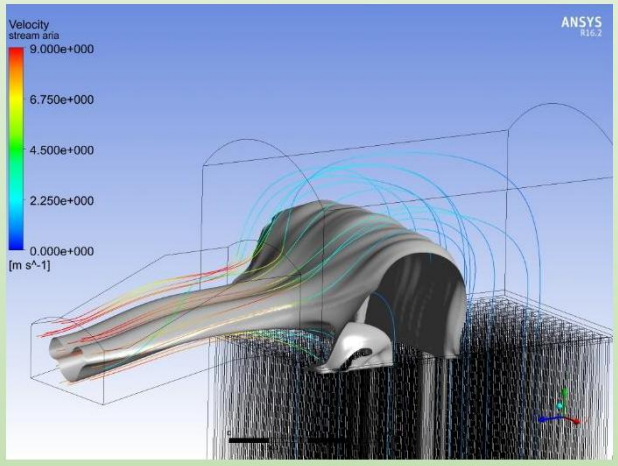
Examples of exhaust gas feeding system optimization design

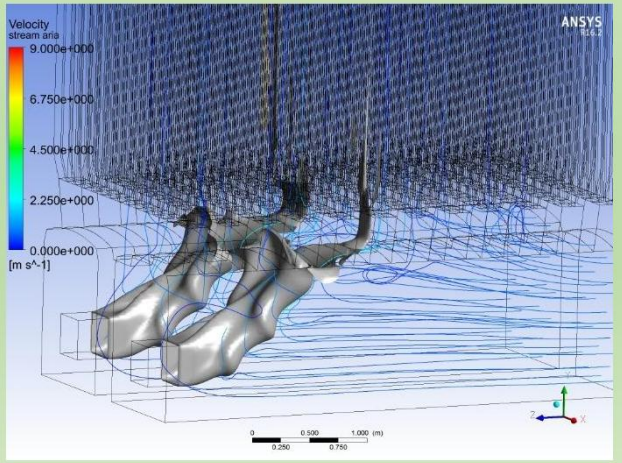
Case 1
«short square duct»



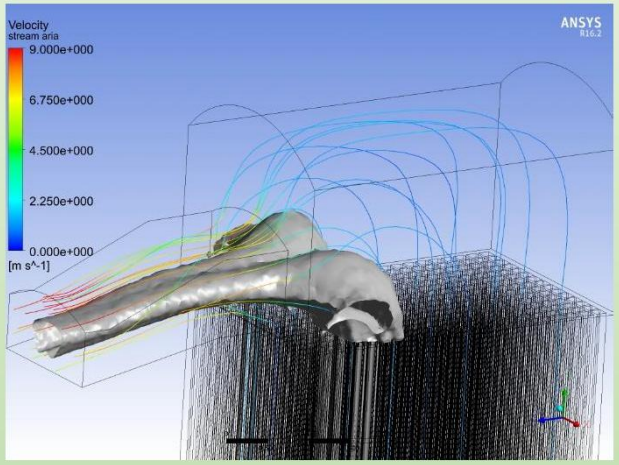


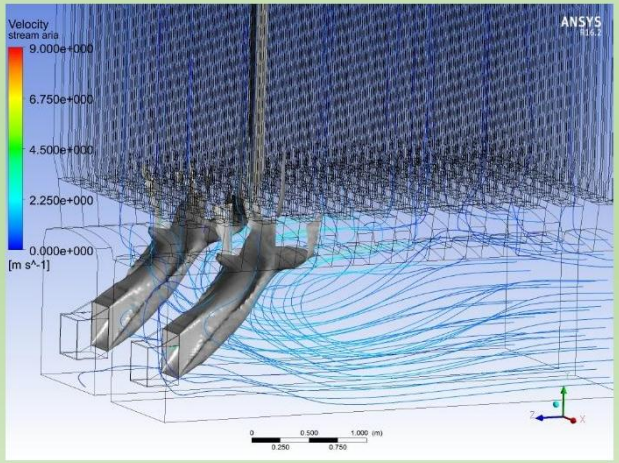
Case 2
«long square duct»



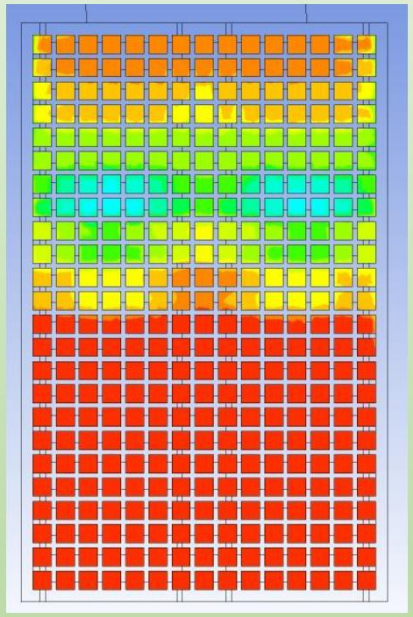
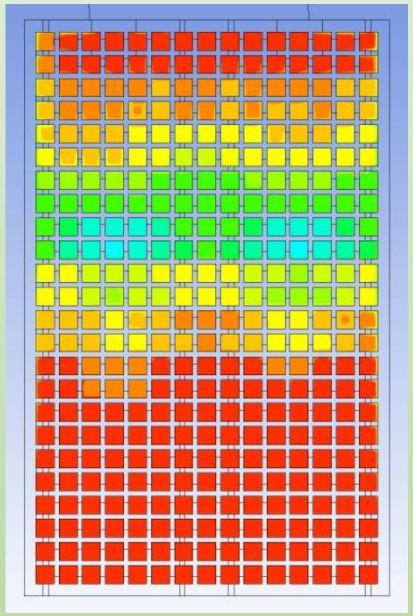
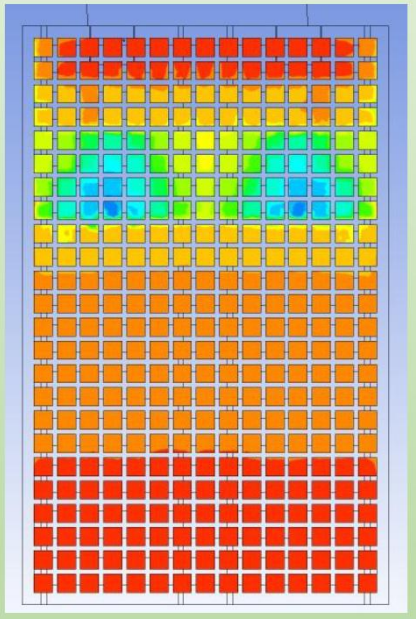
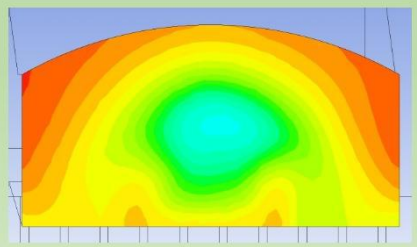
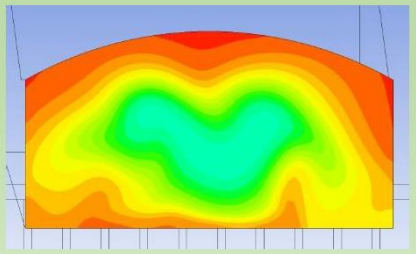
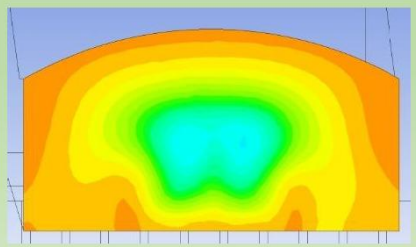


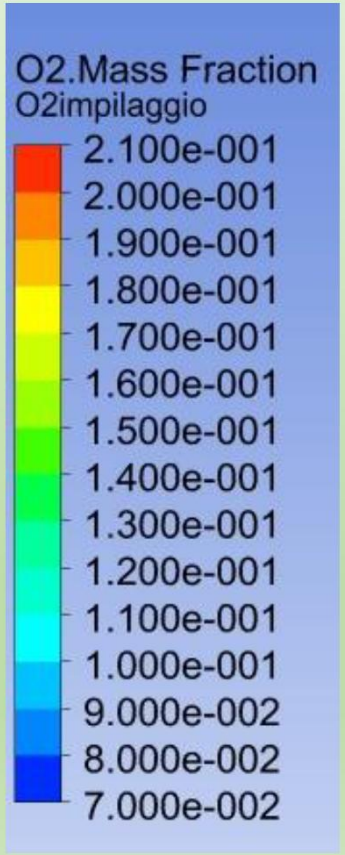
Case 3
«divergent duct»

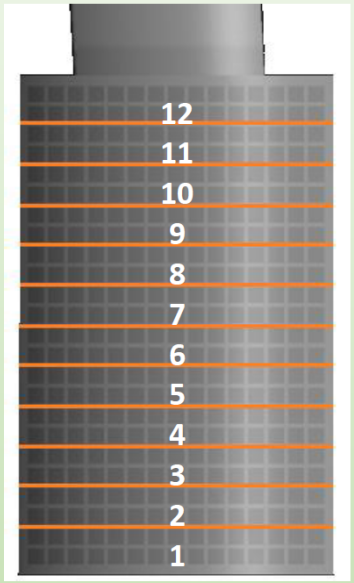




Recirculated waste gas tracking

	Case 1 «short square duct»	Case 2 «long square duct»	Case 3 «divergent duct»
Top of the checkers zone			
Cold Port-neck			




12
11
10
9
8
7
6
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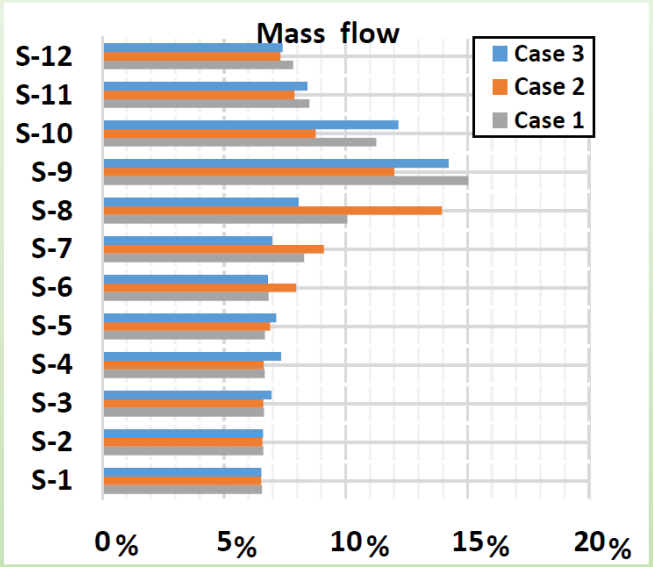
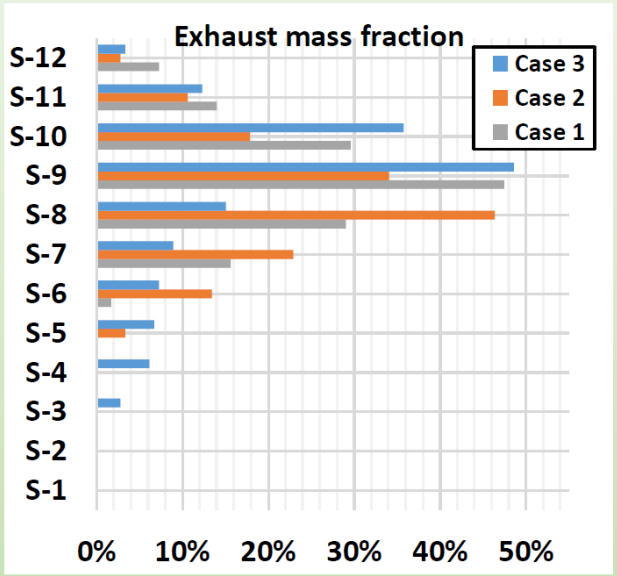
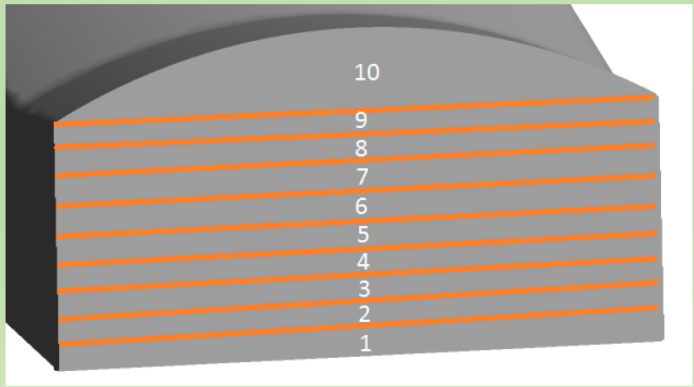
4
3
2
1


Mass flow
S-12
S-11
S-10
S-9
S-8
S-7
S-6
S-5
S-4
S-3
S-2
S-1
Case 3
Case 2
Case 1
0%
5%
10%
15%
20%


Exhaust mass fraction
S-12
S-11
S-10
S-9
S-8
S-7
S-6
S-5
S-4
S-3
S-2
S-1
Case 3
Case 2
Case 1
0%
10%
20%
30%
40%
50%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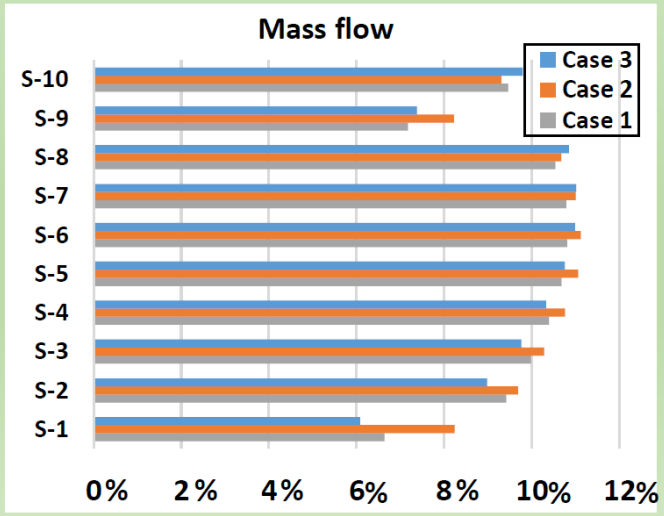
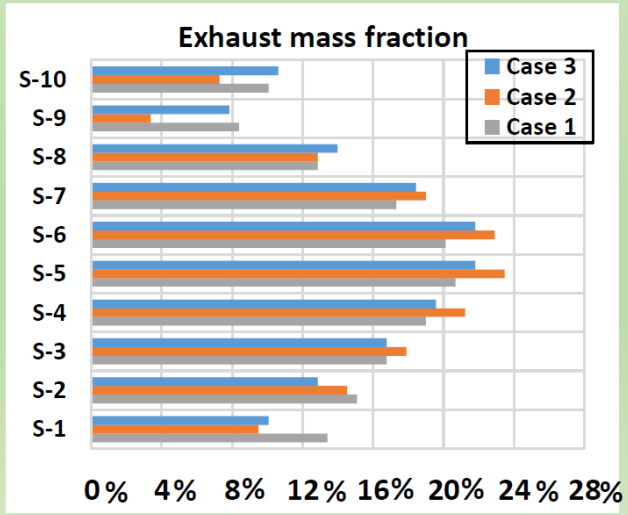
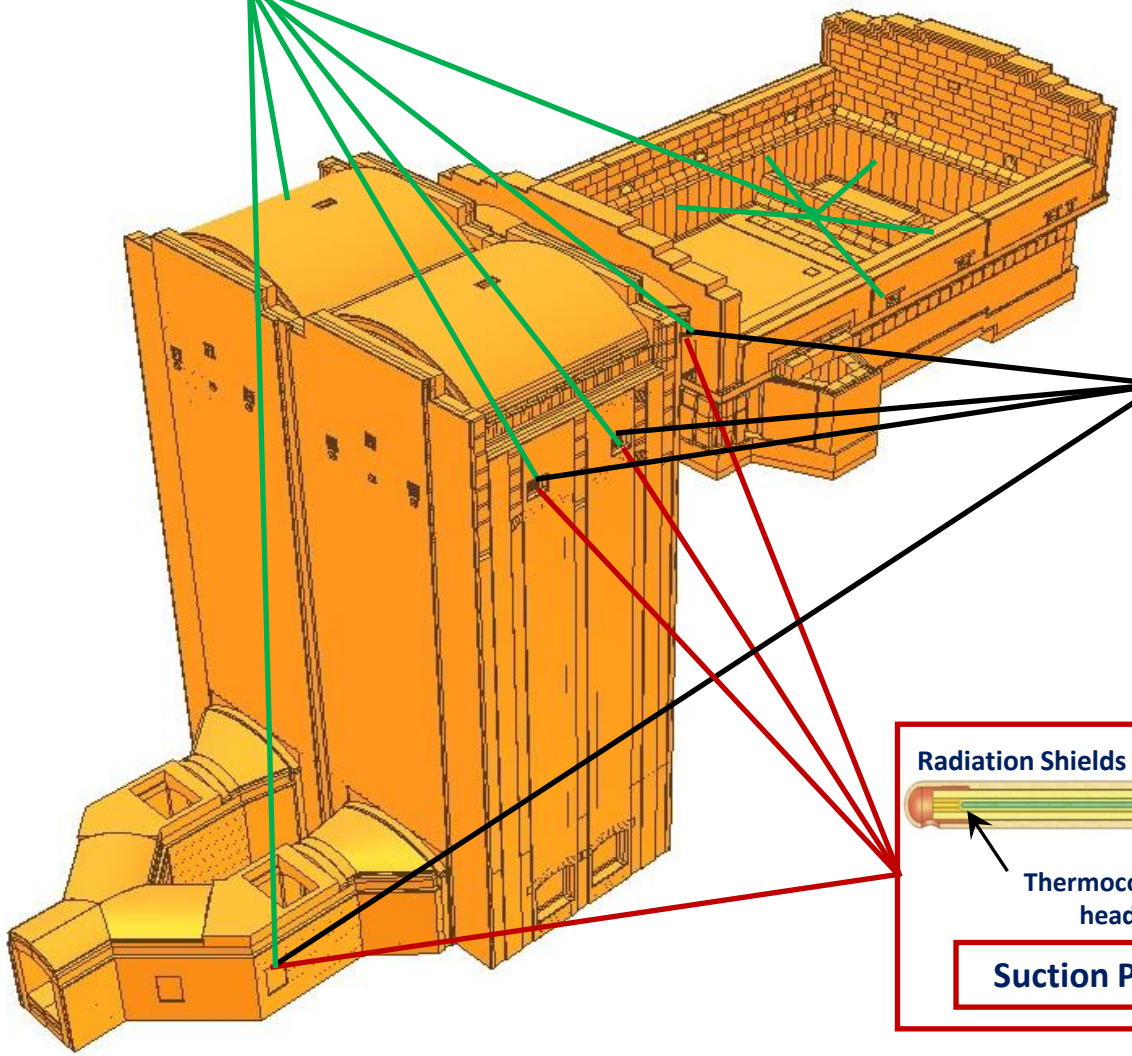
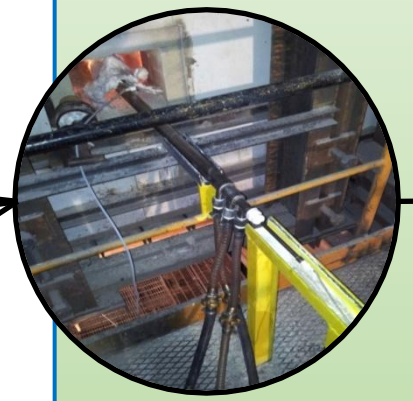

Mass flow
S-10
S-9
S-8
S-7
S-6
S-5
S-4
S-3
S-2
S-1
Case 3
Case 2
Case 1
0%
2%
4%
6%
8%
10%
12%


Exhaust mass fraction
S-10
S-9
S-8
S-7
S-6
S-5
S-4
S-3
S-2
S-1
Case 3
Case 2
Case 1
0%
4%
8%
12%
16%
20%
24%
28%

Emissions and combustion characterization

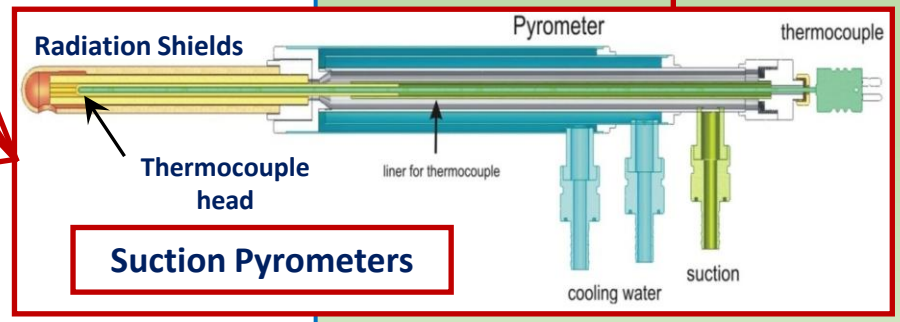
Micromanometers (Pressure Meters)





Cooled Probes

Gas conditioning systems
Multiple gas analyzers
Data acquisition units



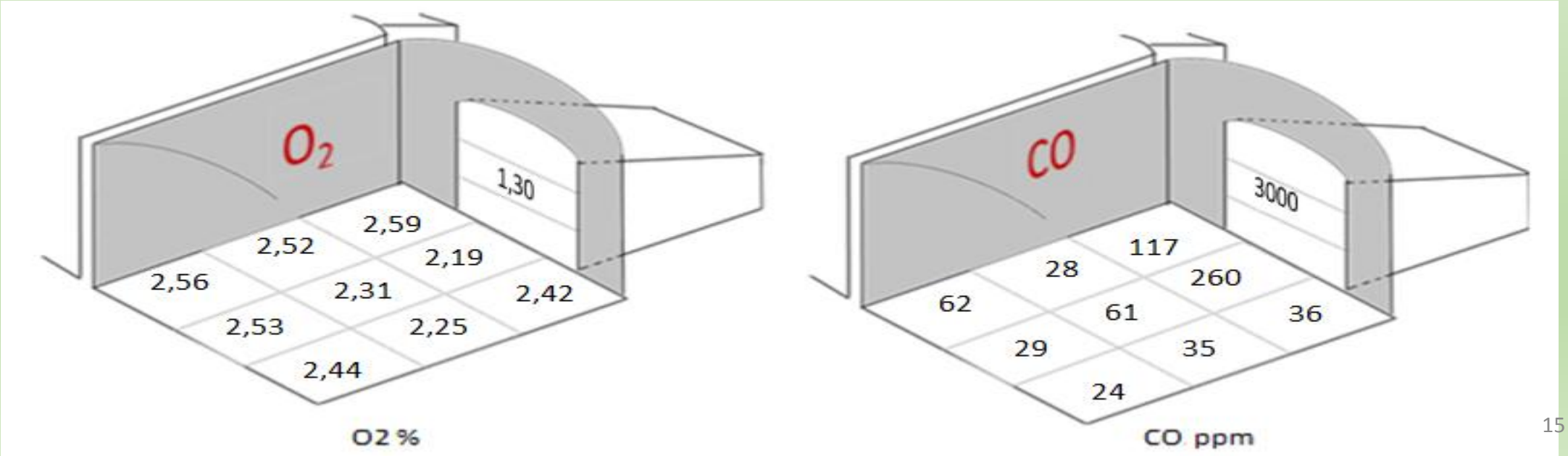
Suction Pyrometers

BASELINE CHARACTERIZATION - Flue gases analysis

The waste gases produced by **Trezzano furnace No. 3** with the recirculation system turned **OFF** were characterized to determine the reference state of combustion.

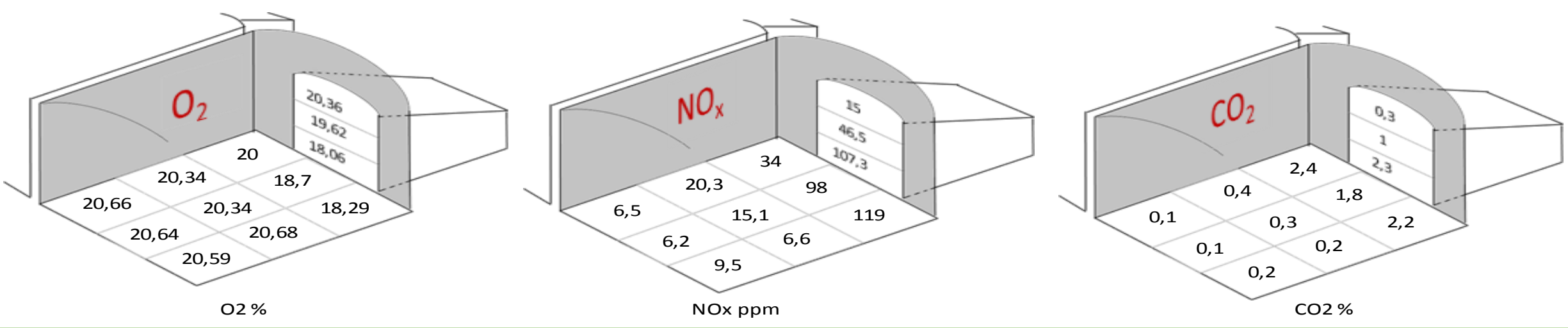
At the top of the regenerator chambers the flue gases stream was mapped just above the checkerworks in 9 different positions, following a 3 x 3 grid, by means of 4 m long probes; in the port neck the probe was placed only in the central position. The results, averaged over several complete inversions, are reported below.

Waste gases recirculation OFF – Flue gases Chamber



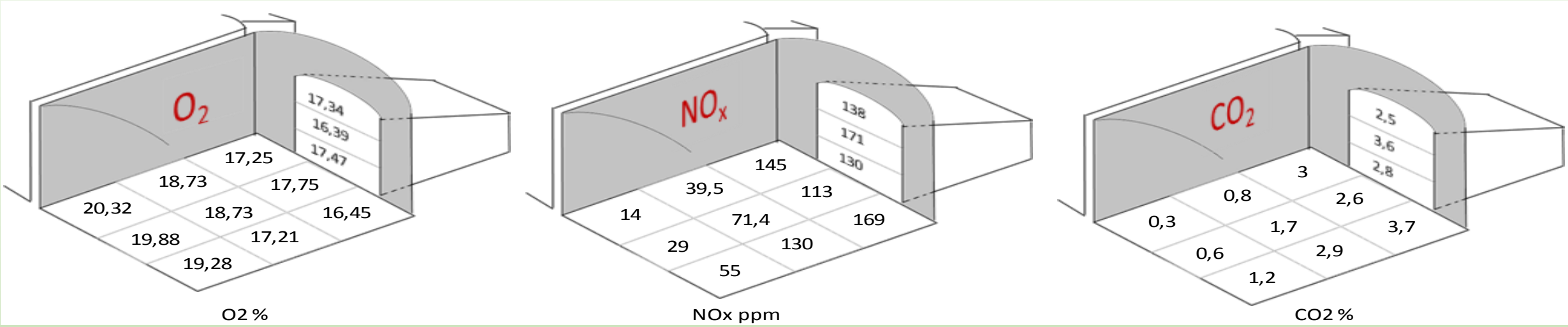
The 4 m long water cooled probes used in the top chamber were operated by three SSV technicians, and kept in the same measurement spot of the grid for at least 5 minutes each, so the whole chamber could be mapped during three successive inversions. The port neck was mapped using a curved ceramic probe with three different orientations (tip facing down, horizontal, tip facing up).

10% waste gases recirculation – Air Chamber

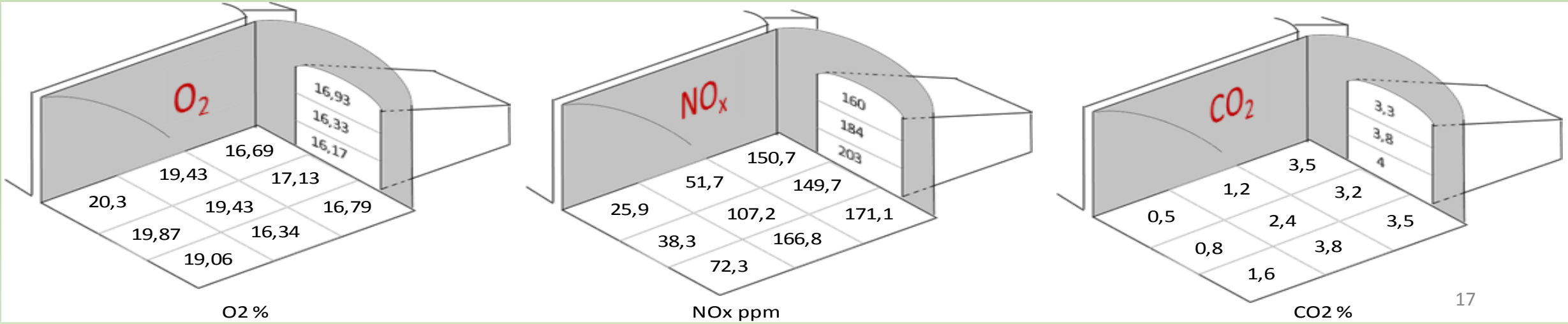


The obtained results show that, at 10% recirculation, in the regenerator flue gases tend to segregate close to the port wall, that is close to the side of the regenerator from which they are injected: they are entrained and brought up by the ascending cold air stream. They also tend to segregate towards the lower part of the port neck.

20% waste gases recirculation – Air Chamber



30% waste gases recirculation – Air Chamber

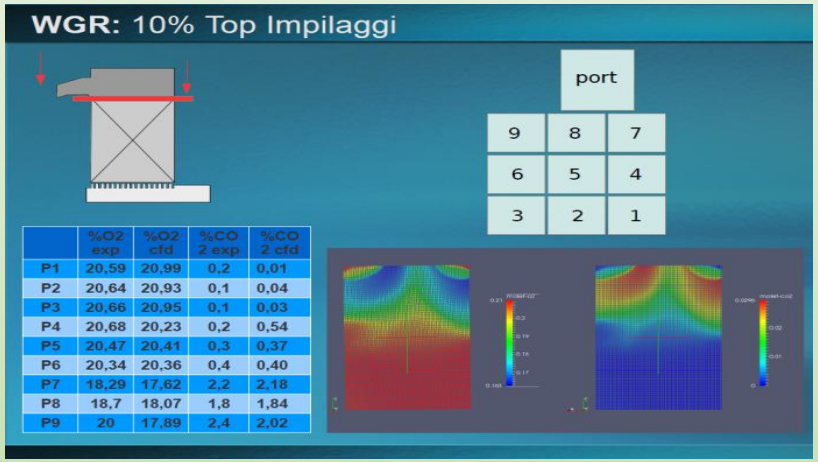


Increasing the recirculated flow rate leads to a more homogeneous spread of flue gases across the whole regenerator packing and, especially, inside the port neck. This is due to the higher injection velocity at the base of the regenerator, that causes a more thorough mixing with cold air before climbing up into the checkerworks.

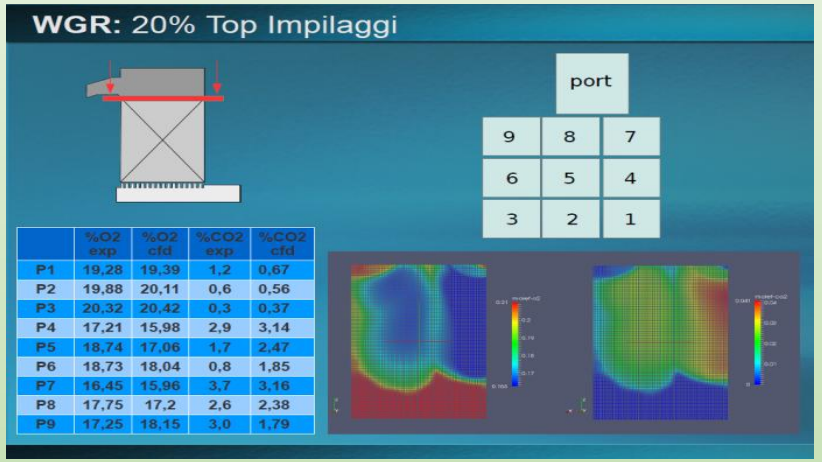
Effects of WG recirculation rate on average NOx levels measured in the chamber (Point 5)								
Chamber Point 5	Recirc nominal flow rate %	O2 ($\%_{vol}$)	NOx ppm	NOx mg/Nmc @ 8% O_2	CO_2 $\%_{vol}$	SO_2 ppm	% Reduction NOx [ppm]	% Reduction NOx [mg/Nmc @ 8%O_2]
DX	0	2,23	1069	1520	15,4	142,1	0,0	**0,0**
DX	10	2,14	1011	1431	15	163,3	5,4	**5,9**
DX	20	2,24	960	1366	14,9	136,5	10,2	**10,1**
DX	30	2,34	924	1322	15,0	134,4	13,6	**13,1**
Chamber Point 5	Recirc nominal flow rate %	O2 ($\%_{vol}$)	NOx ppm	NOx mg/Nmc @ 8% O_2	CO_2 $\%_{vol}$	SO_2 ppm	% Reduction NOx [ppm]	% Reduction NOx [mg/Nmc @ 8%O_2]
SX	0	2,37	935	1339	15,1	160,9	0,0	**0,0**
SX	10	2,23	841	1196	15,4	143,3	10,1	**10,7**
SX	20	2,03	820	1154	15,1	164,1	12,3	**13,9**
SX	30	1,72	755	1045	15,2	170,0	19,3	**22,0**

The compositional maps of combustion air enriched in recirculated off-gases were also used to validate the numerical approach exploited in simulating regenerator chambers and port-necks by CFD modeling.

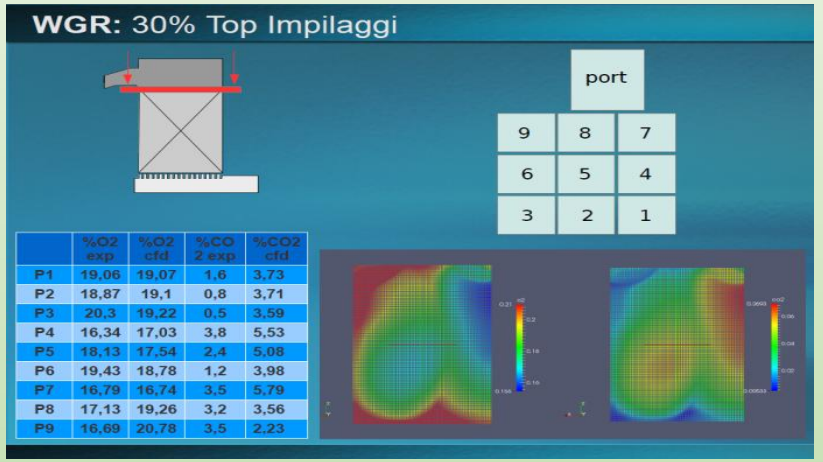
Top regenerators chambers



	%O2 exp	%O2 cfd	%CO 2 exp	%CO 2 cfd
P1	20,59	20,99	0,2	0,01
P2	20,64	20,93	0,1	0,04
P3	20,66	20,95	0,1	0,03
P4	20,68	20,23	0,2	0,54
P5	20,47	20,41	0,3	0,37
P6	20,34	20,36	0,4	0,40
P7	18,29	17,62	2,2	2,18
P8	18,7	18,07	1,8	1,84
P9	20	17,89	2,4	2,02



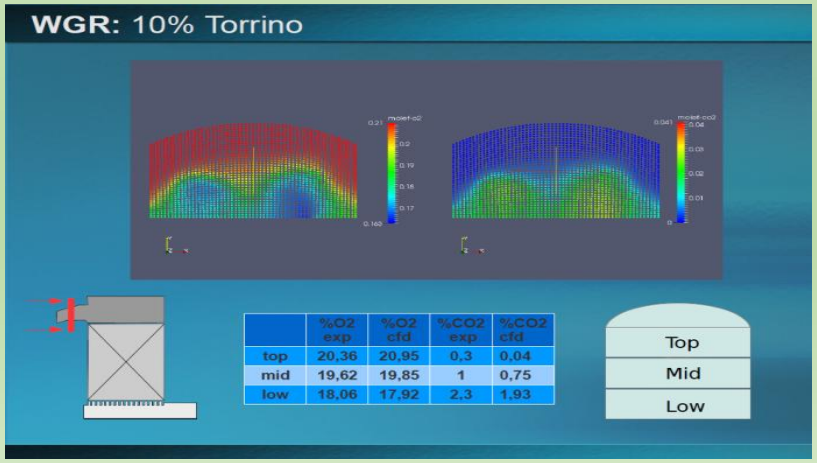
	%O2 exp	%O2 cfd	%CO2 exp	%CO2 cfd
P1	19,28	19,39	1,2	0,67
P2	19,88	20,11	0,6	0,56
P3	20,32	20,42	0,3	0,37
P4	17,21	15,98	2,9	3,14
P5	18,74	17,06	1,7	2,47
P6	18,73	18,04	0,8	1,85
P7	16,45	15,96	3,7	3,16
P8	17,75	17,2	2,6	2,38
P9	17,25	18,15	3,0	1,79



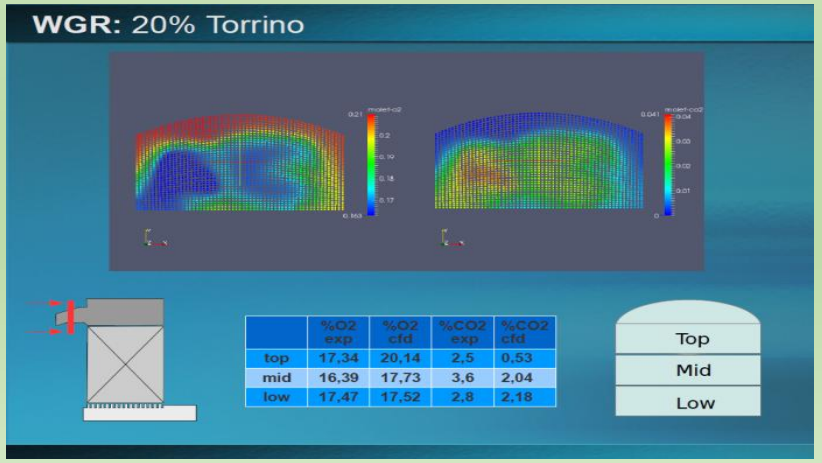
	%O2 exp	%O2 cfd	%CO 2 exp	%CO2 cfd
P1	19,06	19,07	1,6	3,73
P2	18,87	19,1	0,8	3,71
P3	20,3	19,22	0,5	3,59
P4	16,34	17,03	3,8	5,53
P5	18,13	17,54	2,4	5,08
P6	19,43	18,78	1,2	3,98
P7	16,79	16,74	3,5	5,79
P8	17,13	19,26	3,2	3,56
P9	16,69	20,78	3,5	2,23

Port neck

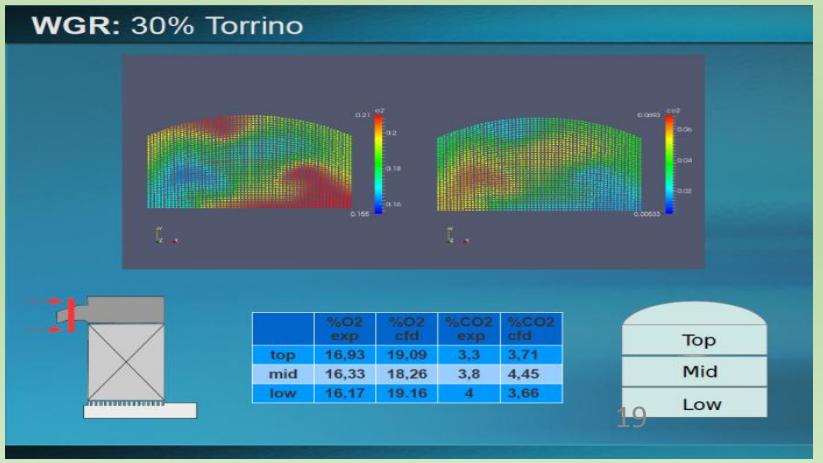
10% 20% 30%



	%O2 exp	%O2 cfd	%CO2 exp	%CO2 cfd
top	20,36	20,95	0,3	0,04
mid	19,62	19,85	1	0,75
low	18,06	17,92	2,3	1,93

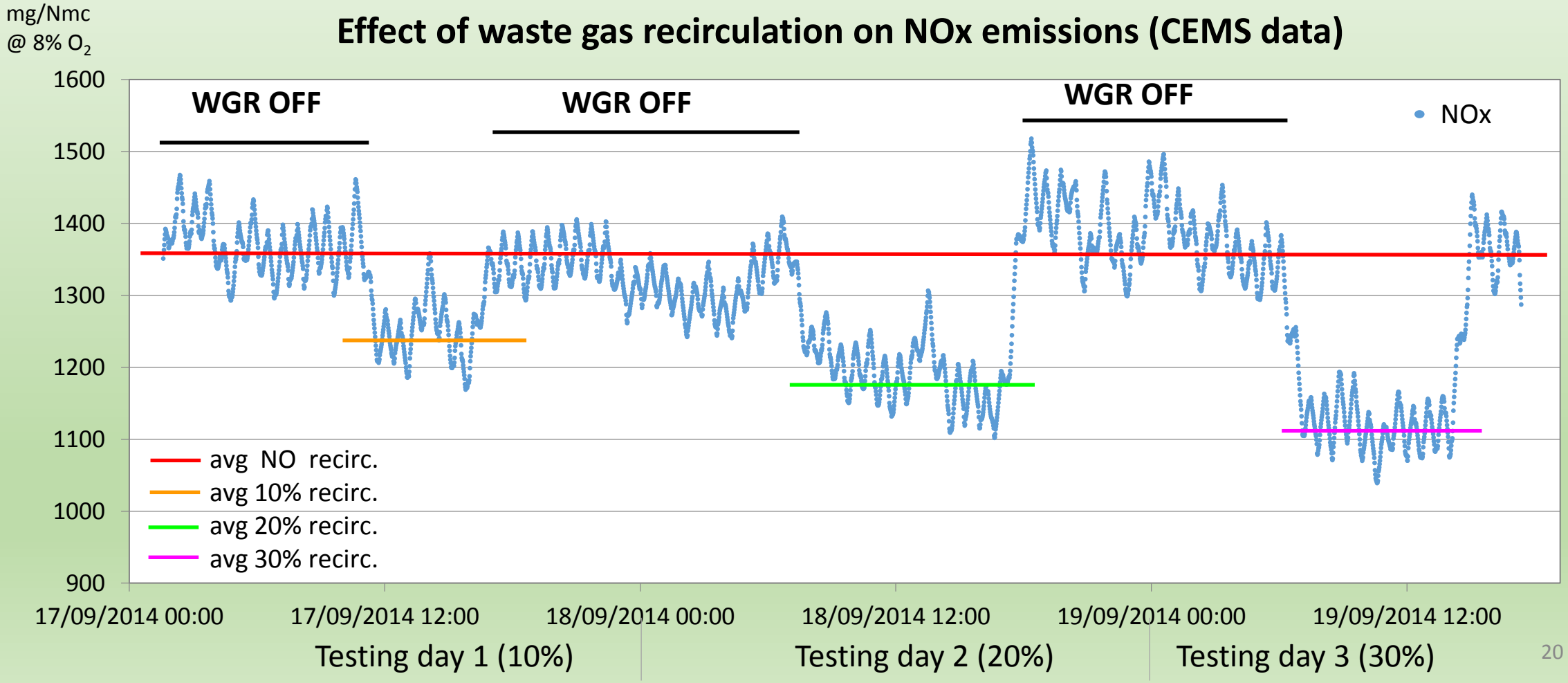


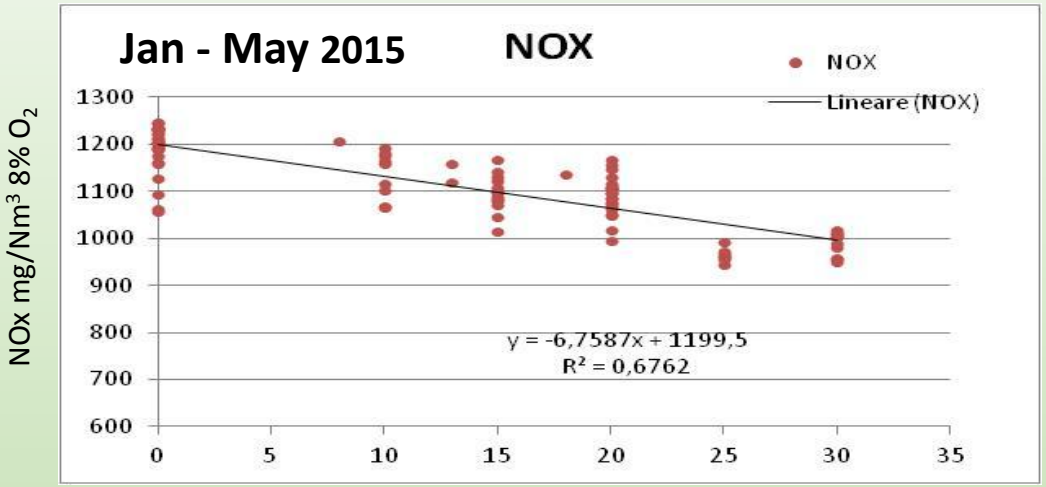
	%O2 exp	%O2 cfd	%CO2 exp	%CO2 cfd
top	17,34	20,14	2,5	0,53
mid	16,39	17,73	3,6	2,04
low	17,47	17,52	2,8	2,18



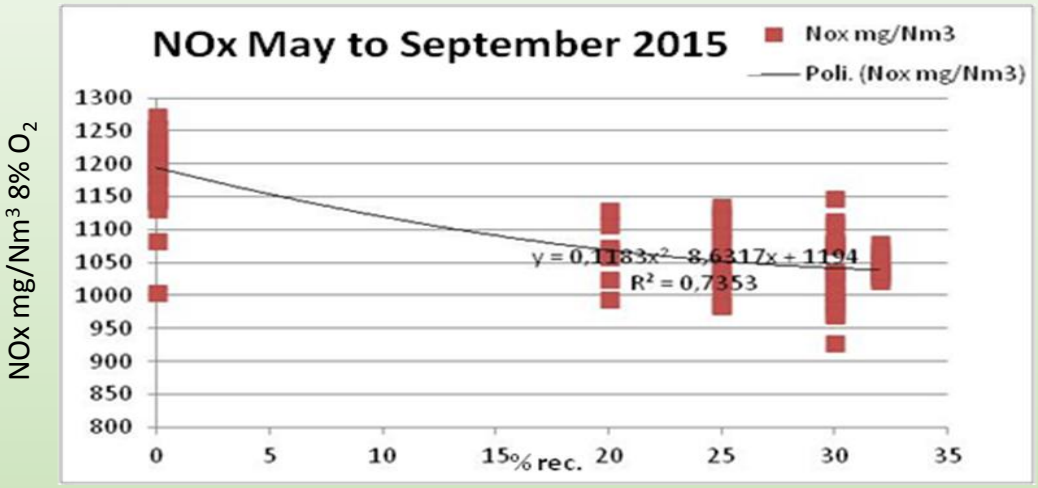
	%O2 exp	%O2 cfd	%CO2 exp	%CO2 cfd
top	16,93	19,09	3,3	3,71
mid	16,33	18,26	3,8	4,45
low	16,17	19,16	4	3,66

As expected, the **higher** the **recirculated off gases flow rate**, the **stronger** the effect on **NOx reduction**. The positive results of the PRIME Glass recirculation system appear even more evident from the CEMS data, where in the days of testing the NOx emission levels exhibit considerable drops, proportional in depth to the percentage of recirculation.

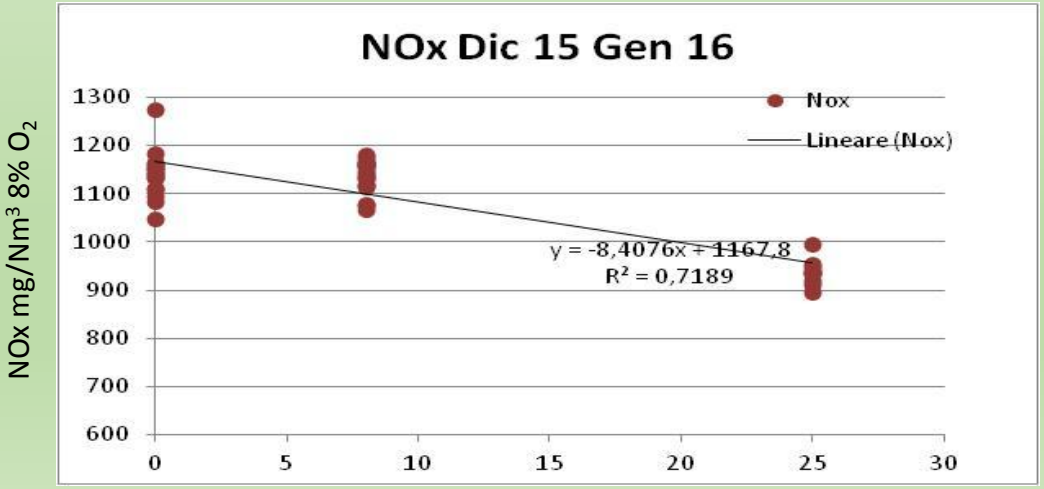




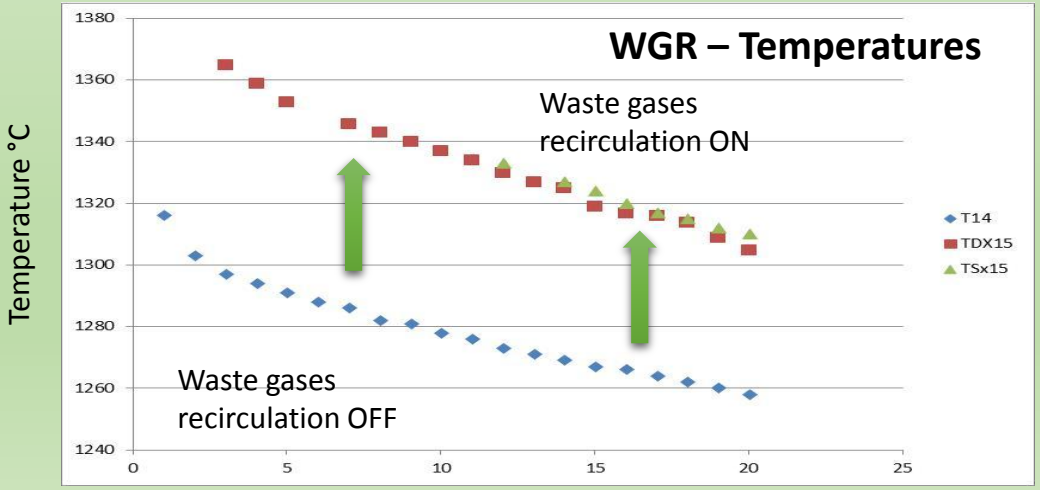
Waste gas Recycling %



Waste gas Recycling %

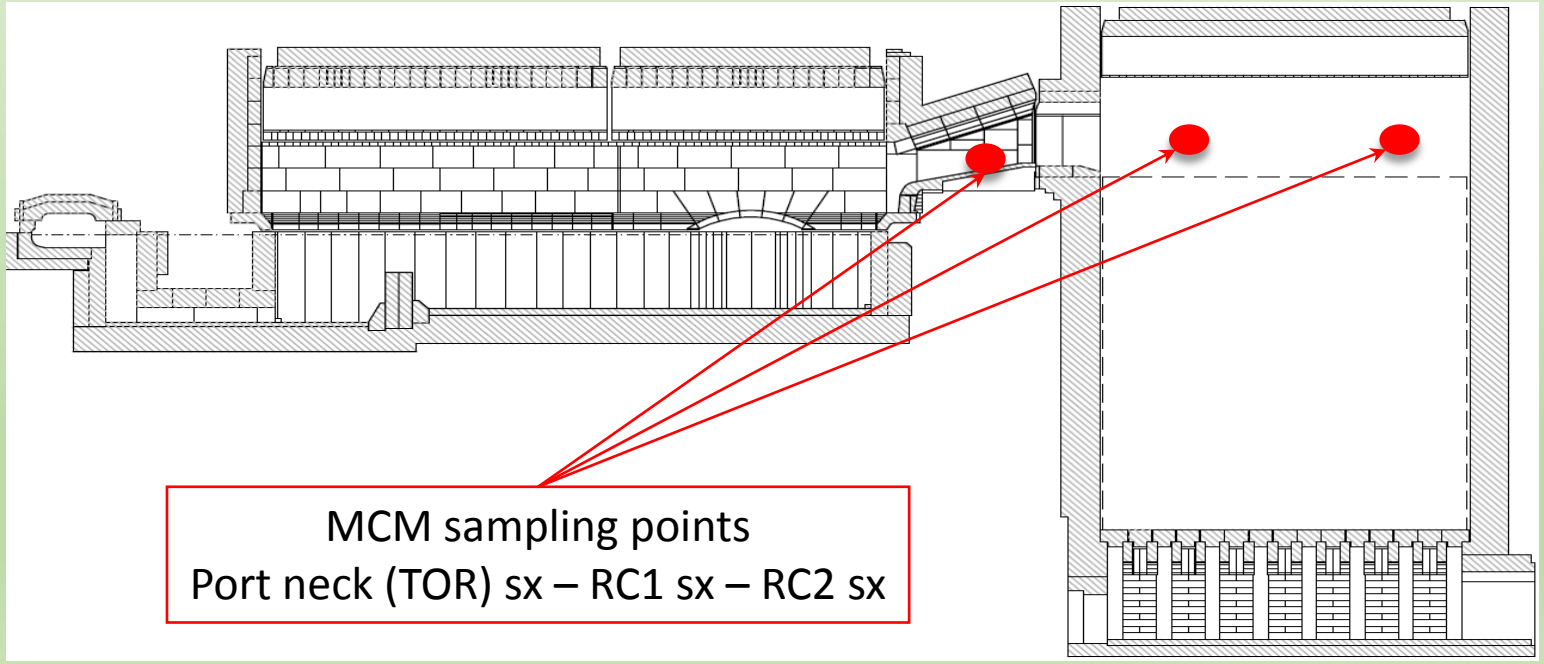


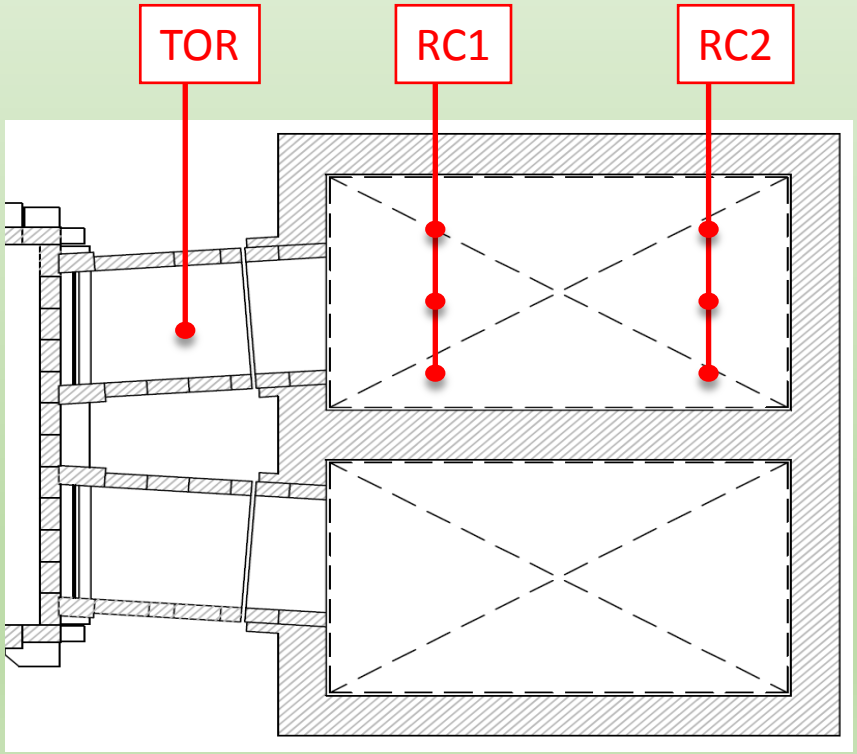
Waste gas Recycling %



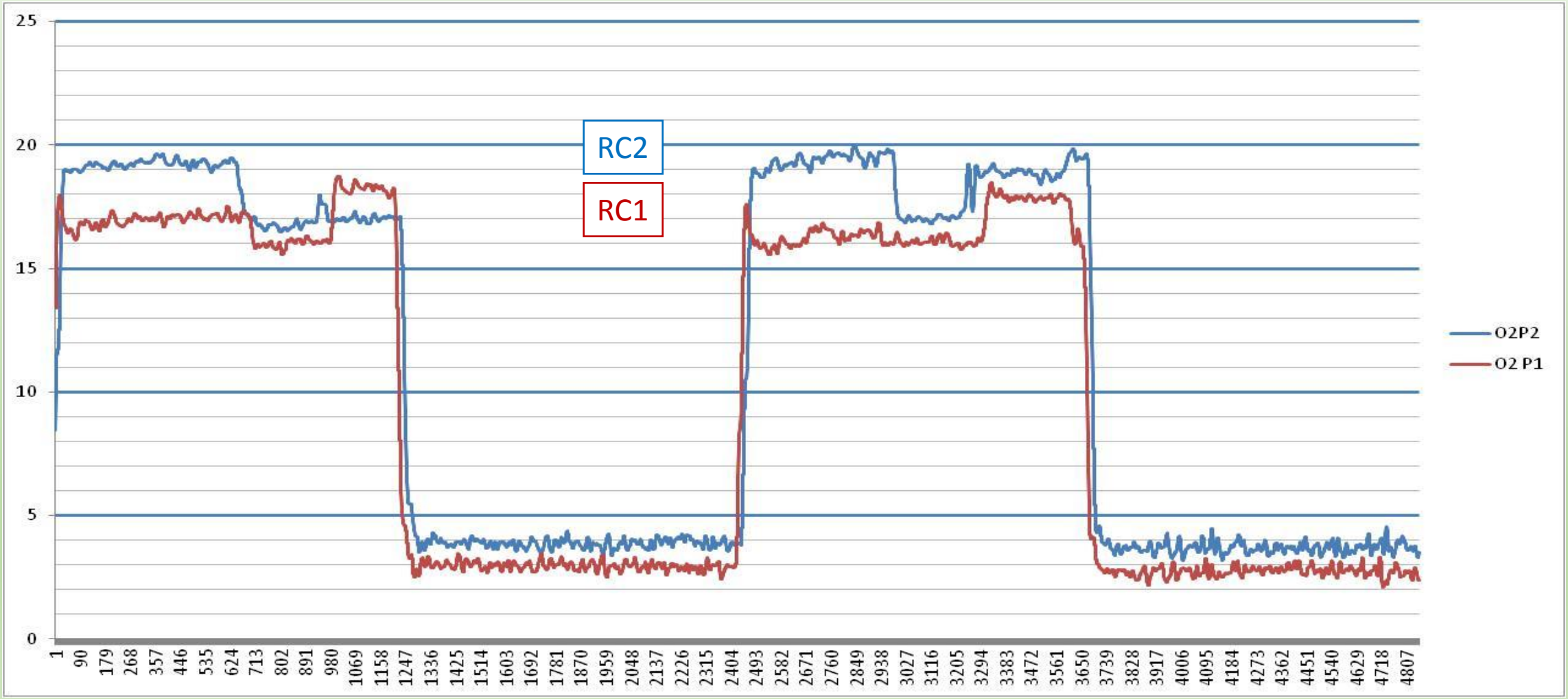
minute

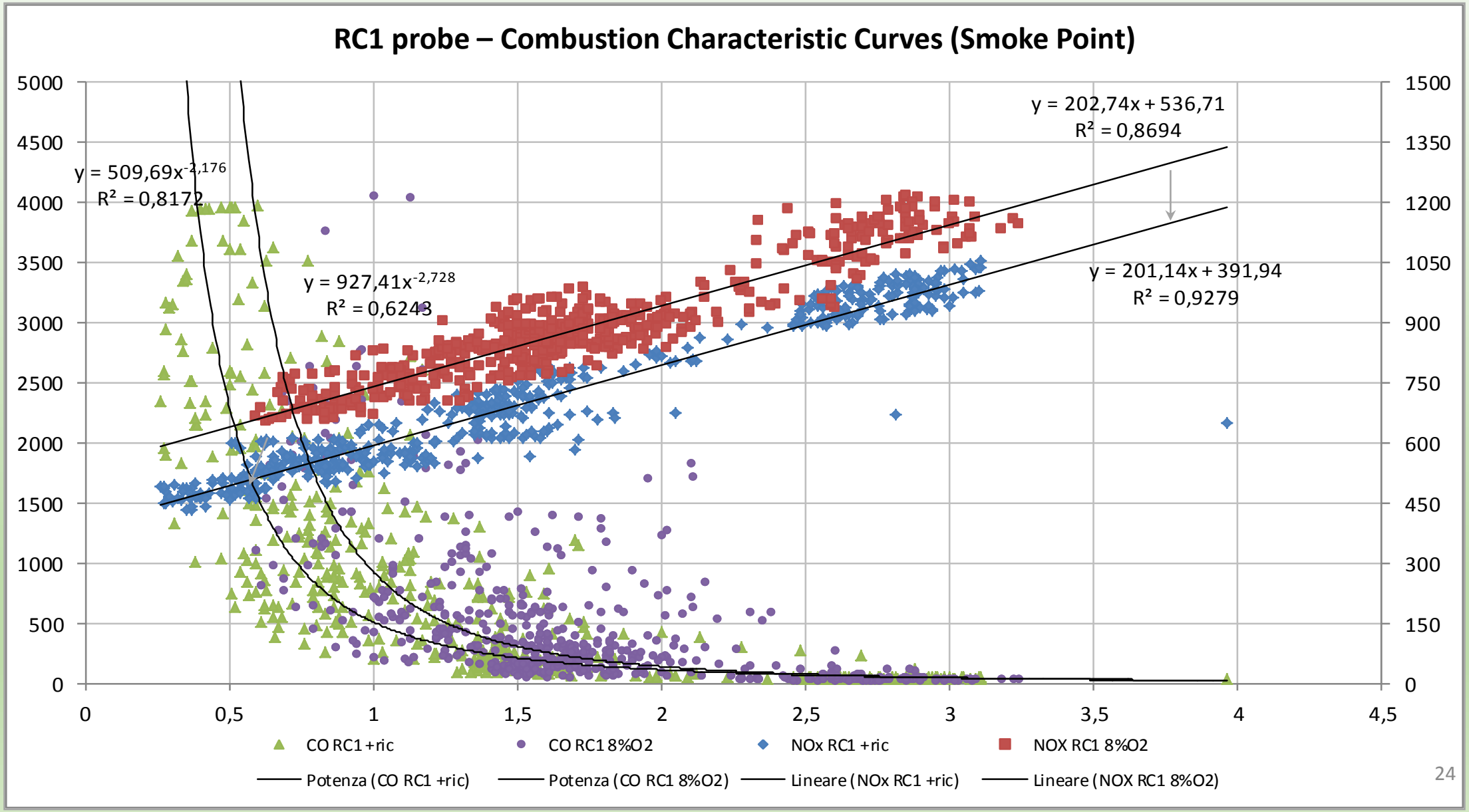
The second full scale embodiment of a PRIME Glass Strategic **Waste Gases Recirculation** unit has been installed at the bottom of the regenerator of Vetri Speciali SpA **San Vito al Tagliamento** (PN) (Italy) **Furnace No. 2**.





Grid Characterization – Top Chamber (Air phase)




RC1 probe – Combustion Characteristic Curves (Smoke Point)
y = 509,69x^-2,176
R² = 0,8172
y = 927,41x^-2,728
R² = 0,6243
y = 202,74x + 536,71
R² = 0,8694
y = 201,14x + 391,94
R² = 0,9279
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1500
1350
1200
1050
900
750
600
450
300
150
0
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
CO RC1 +ric
CO RC1 8%O2
NOx RC1 +ric
NOX RC1 8%O2
Potenza (CO RC1 +ric)
Potenza (CO RC1 8%O2)
Lineare (NOx RC1 +ric)
Lineare (NOX RC1 8%O2)

Prime Glass Life project

Port neck (TOR) measurement

WGR 0%	WGR 22%	WGR 40%
O2R0	O2	O2
COR0	CO	CO
NoxR0	Nox	Nox

Lower NOx production and more stable combustion conditions

Prime Glass Life project

Regenerator chamber (RC1) measurement

WGR 0%	WGR 22%	WGR 40%
RC1 O2 R0	RC1 O2 R22	RC1 O2 R40
RC1 CO R0	RC1 CO R22	RC1 CO R4
RC1 NOx R0	RC1 NOx R22	RC1 NOx R40

Lower NOx production and more stable combustion conditions

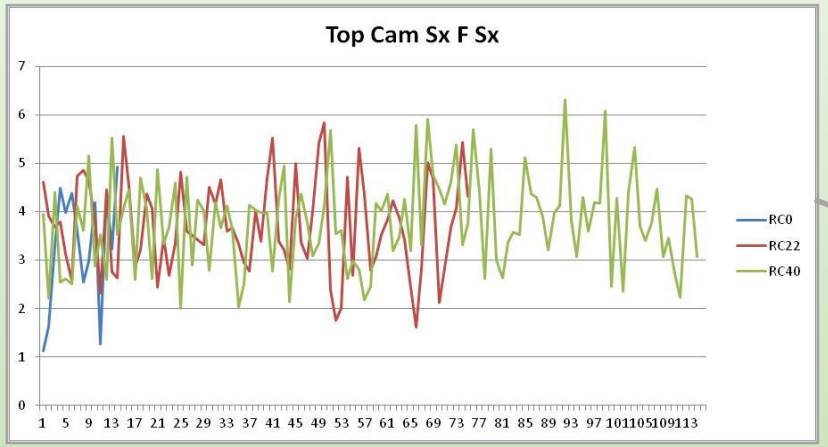
Port neck probe measurements (TOR)

Port Neck	(TOR)	WGR OFF	WGR 22%	WGR 40%
O_2 %	Average	3,01	2,73	2,15
	Sigma	0,48	0,35	0,35
CO ppm	Average	2070	1564	2032
	Sigma	1193	1002	968
NOx mg/Nm^3 8%O_2	Average	1113	1004	829
	Sigma	112	81	55

Regenerator Chamber measurements (RC1)

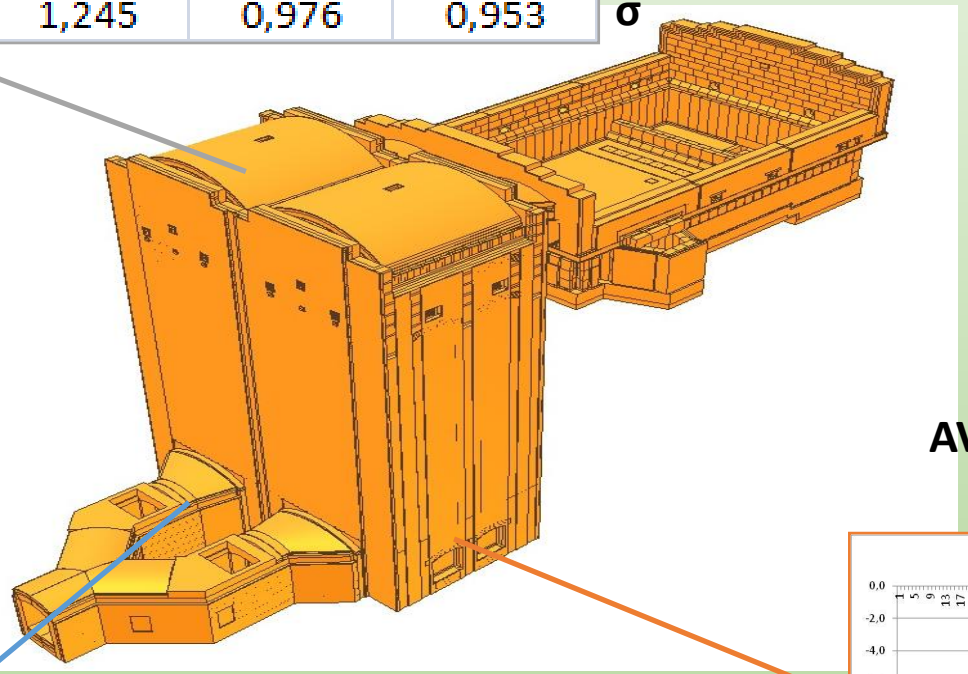
Regenerator	(RC1)	WGR OFF	WGR 22%	WGR 40%
O_2 %	Average	3,04	2,86	2,43
	Sigma	0,18	0,16	0,11
CO ppm	Average	1258	1073	1026
	Sigma	614	584	451
NOx mg/Nm^3 8%O_2	Average	1202	1063	874
	Sigma	112	66	48

Pressures evaluation



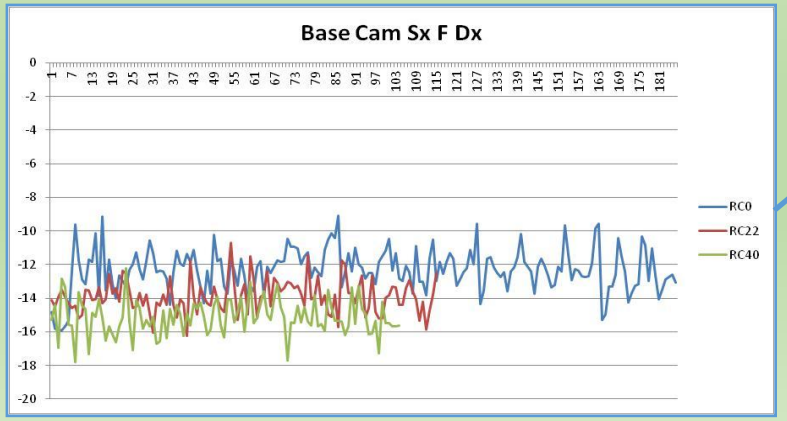
RC0	RC22	RC40
3,29	3,70	3,79
1,245	0,976	0,953

AVG
σ



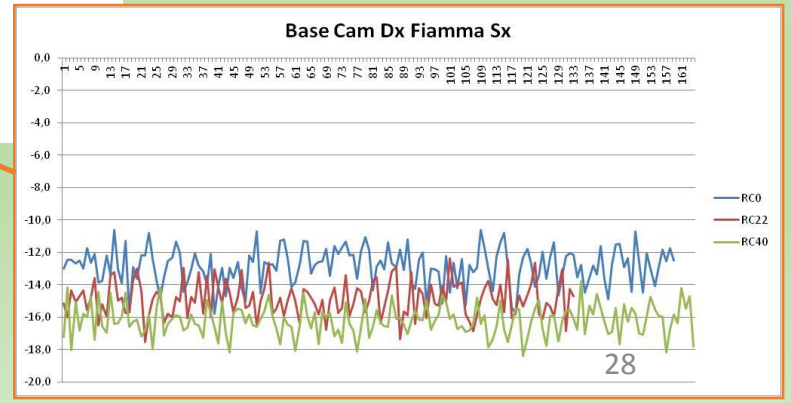
At high WGR% the furnace pressures climb up due to a higher amount of gases flowing through the system; more stable values were observed (lower σ) .

	RC0	RC22	RC40
AVG	-12,85	-14,87	-16,19
σ	1,14	1,08	0,94



RC0	RC22	RC40
-12,32	-13,92	-15,14
1,263	0,985	1,055

AVG
σ



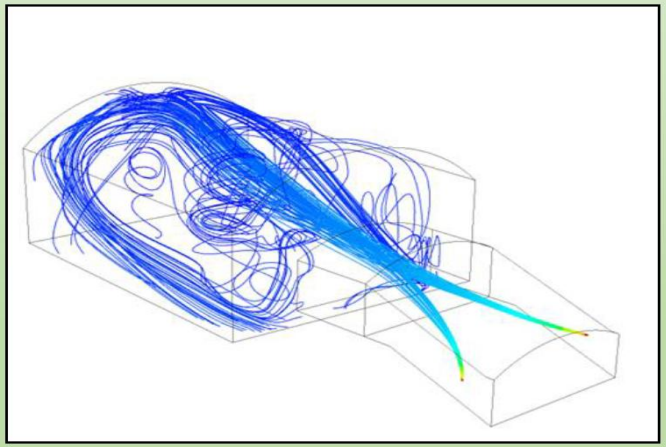
Air Staging Techniques

PRIME Glass Project: high efficiency air staging – DESIGN

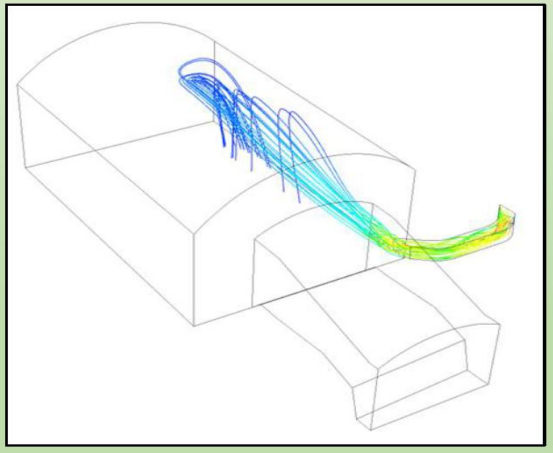
A well known Primary Measure to reduce NOx emissions produced by glass melting furnaces is combustion staging by means of secondary air injection, usually called ***Air Staging***.

Excess air in the furnace is kept at a minimum value (compatibly with satisfactory control over glass quality, color and fining), leading to less production of thermal NOx, but increased CO levels in the port. This residual CO is then oxidized at lower temperature in the port neck and top of regenerator by injection of “secondary” air.

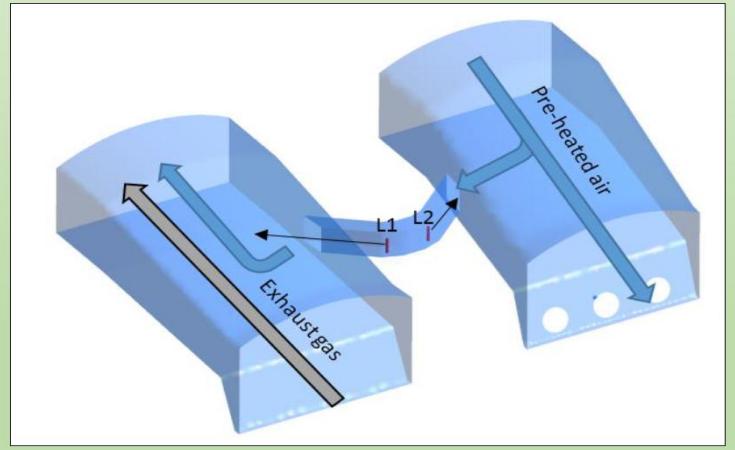
COLD Air Staging



HOT Air Staging



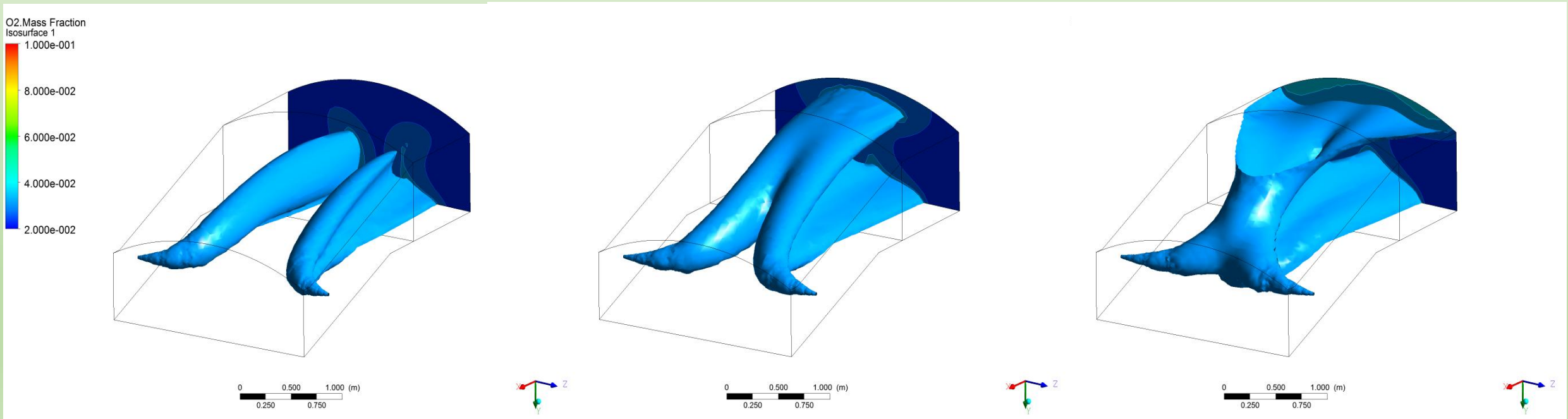
HYBRID Air Staging



system development

Cold air staging – CFD MODELING

The CFD modeling, about the Air Staging, has been an indispensable tool in all phases of **system development**.
The CFD modeling has in the first place the purpose to verify the **correct mixing between waste gas and bypass air**; secondly it is useful for the estimation of the effects on the thermal performance of the furnace.

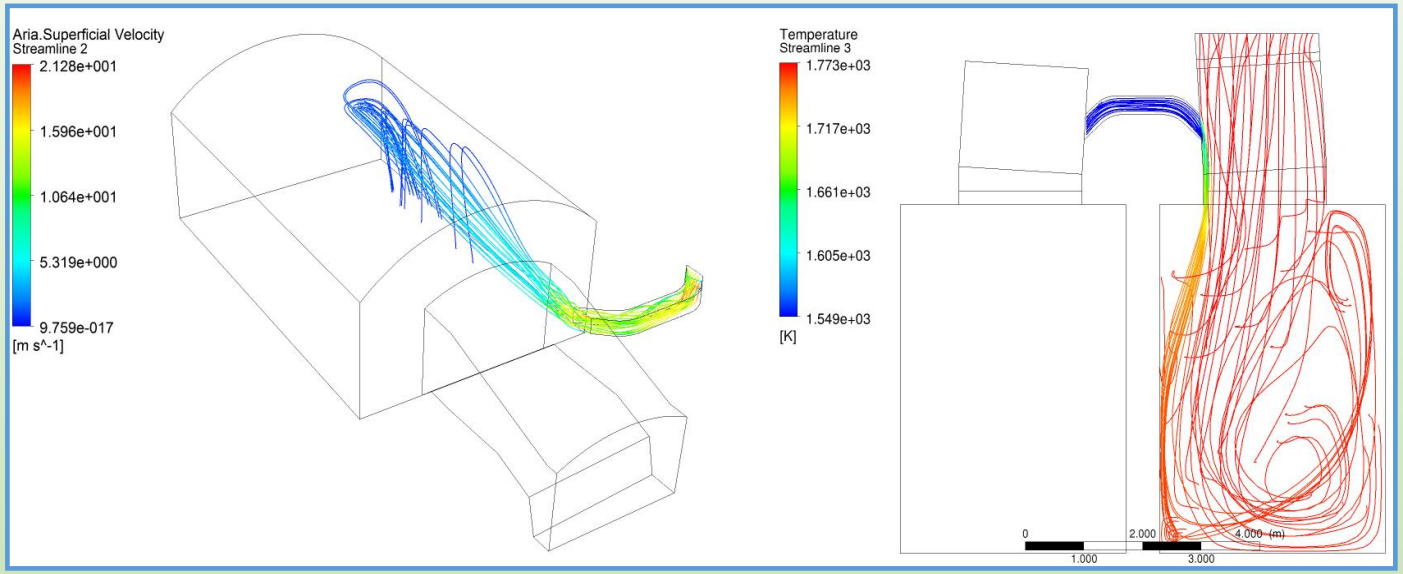


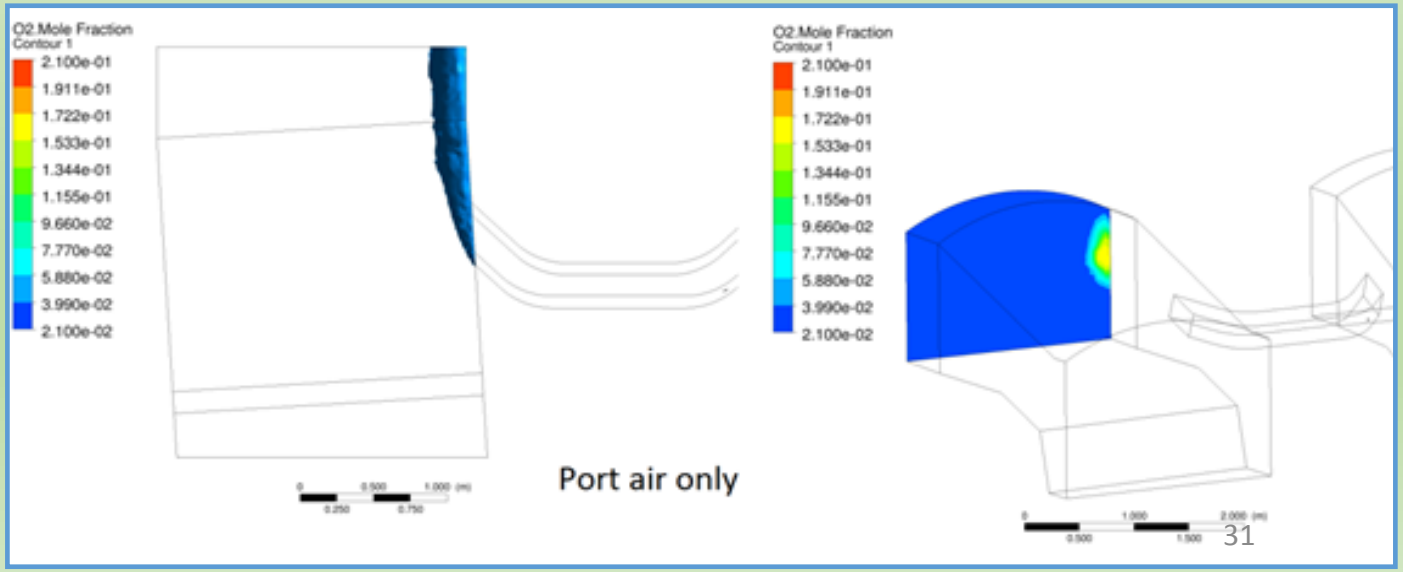
Hot air staging – CFD MODELING

Hot air transfer between the ports, naturally induced by the pressure gradient, has been modeled via CFD simulations, and the results show that its **mixing with flue gases is not sufficient** to guarantee a complete combustion of CO and other unburnt molecules coming from the furnace.

This is due to the **slow velocity** of the drawn preheated air, that is thus "pushed aside" on the internal wall by the waste gases stream, which is faster and has also a higher volumetric flow rate.

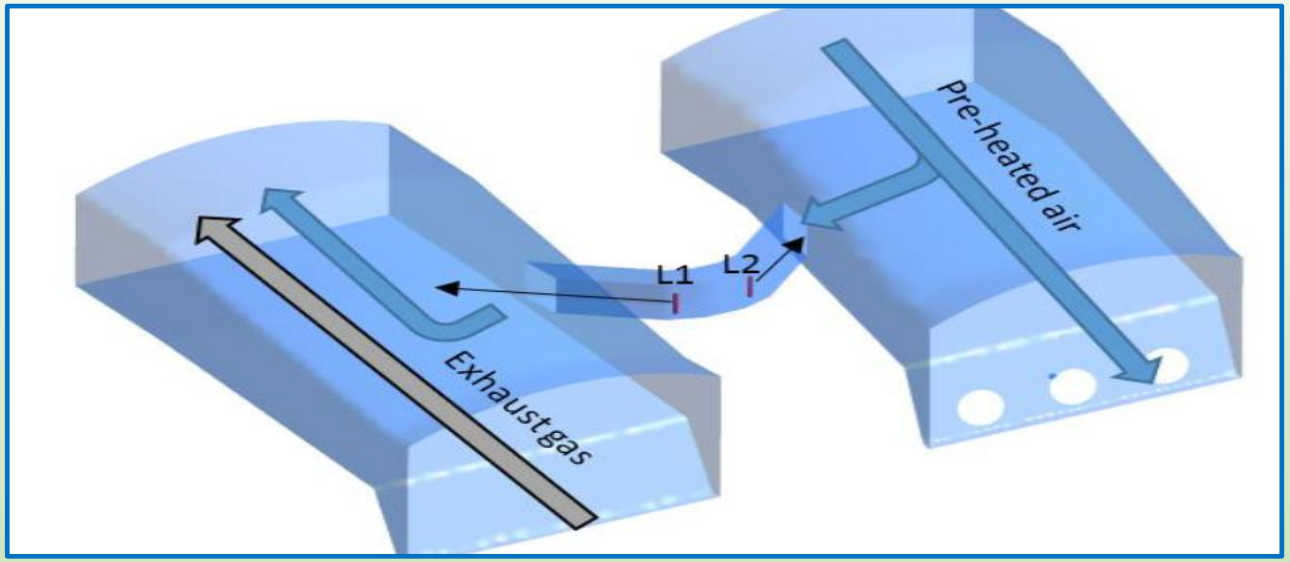
To achieve a successful air staging, hot air needs to be accelerated at higher speed into the port neck by some external means.

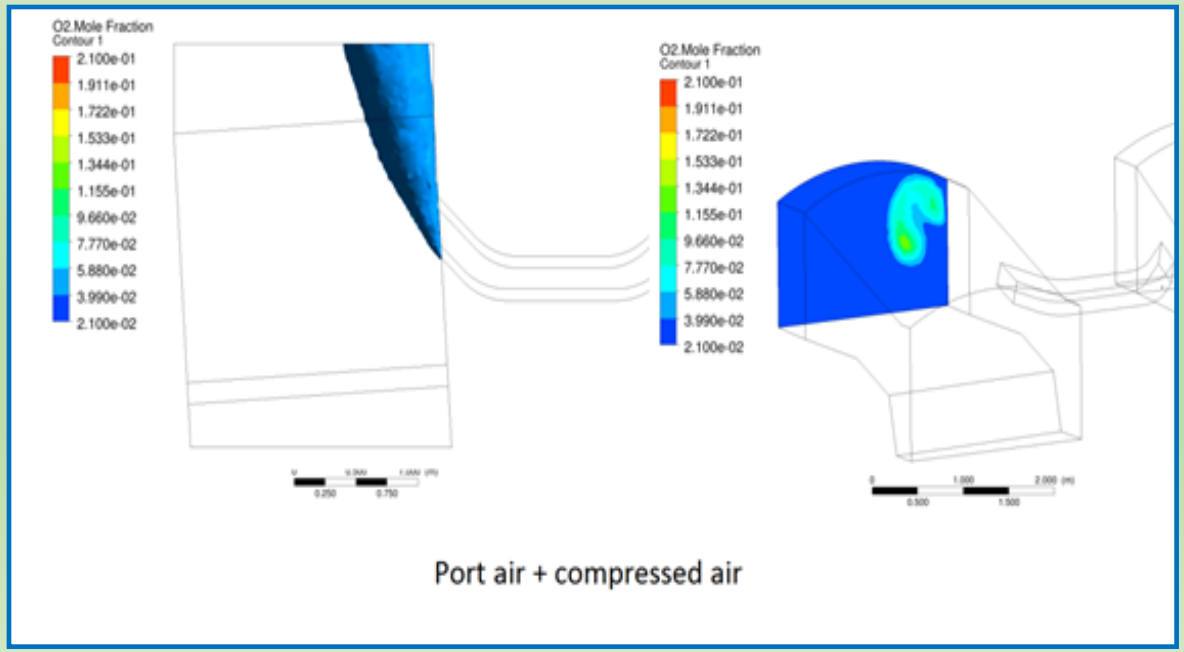


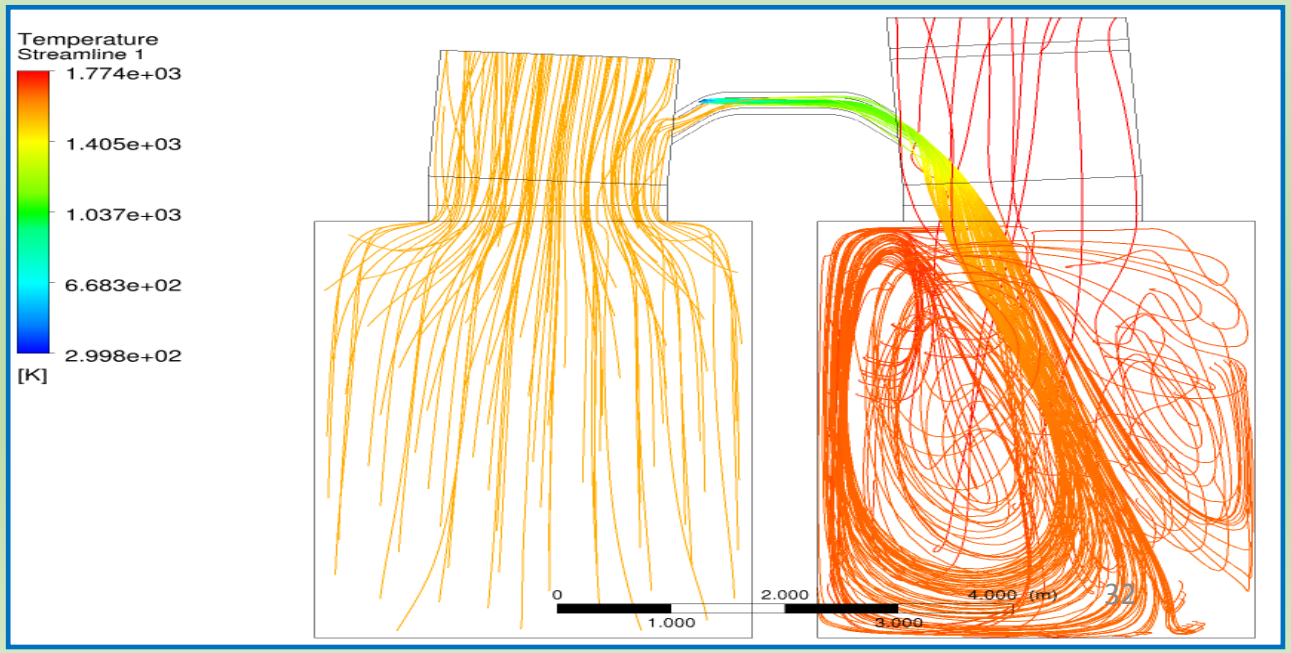


Hybrid air staging – CFD MODELING

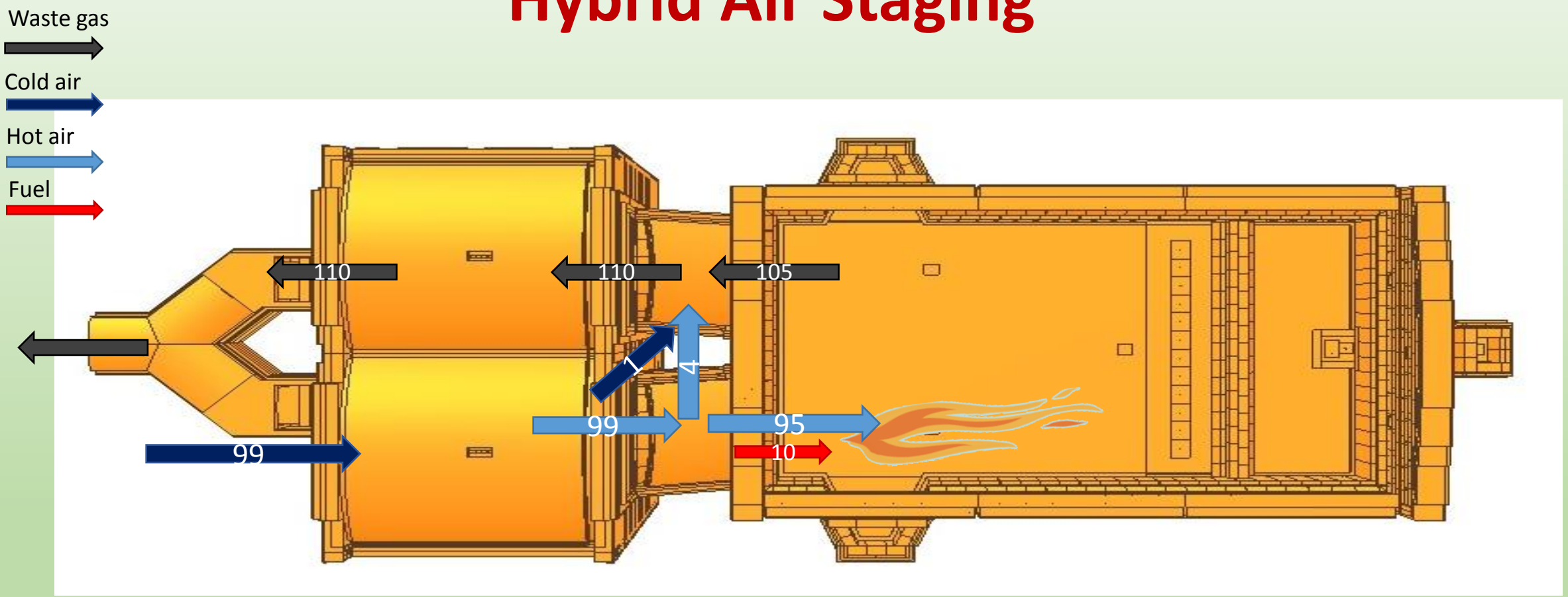
Using a high velocity – low flow rate **cold compressed air jet** to **propel** the extracted **preheated air** toward the opposite port neck would yield a much higher stream velocity without lowering too much the final temperature of the WG







Hybrid Air Staging

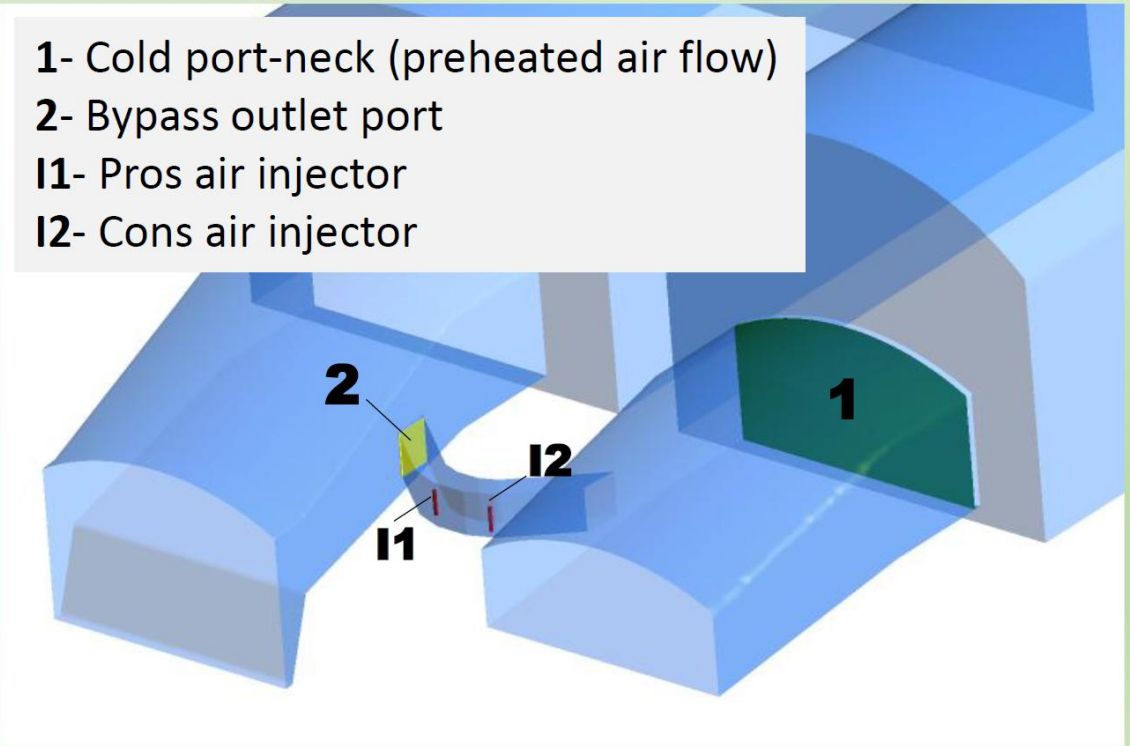


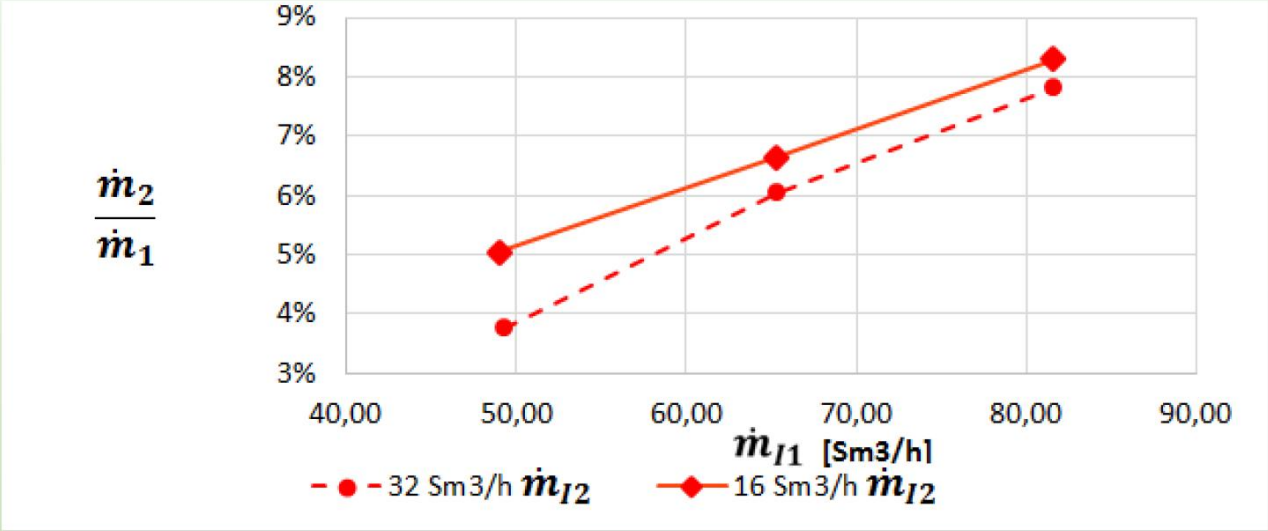
The reported percentage numbers are referred to total air flow rate and represent only an explanatory example of HAS settings

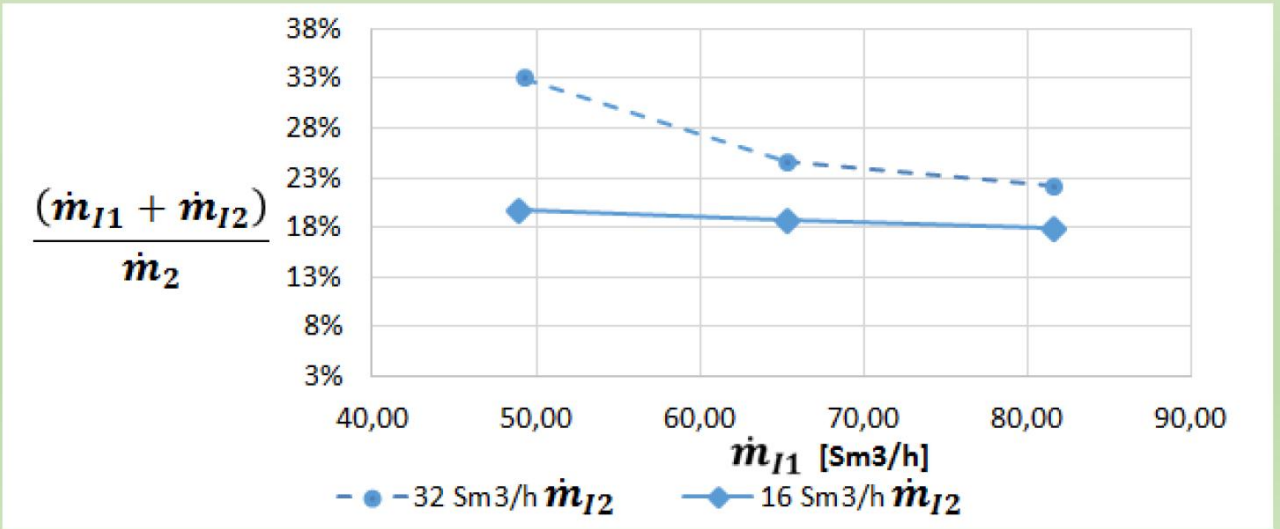
Hybrid Air Staging

The system was successfully installed in Bormioli Rocco SpA plant of Altare (SV) and all tests (Thermal Balances and emissions characterizations) were performed.

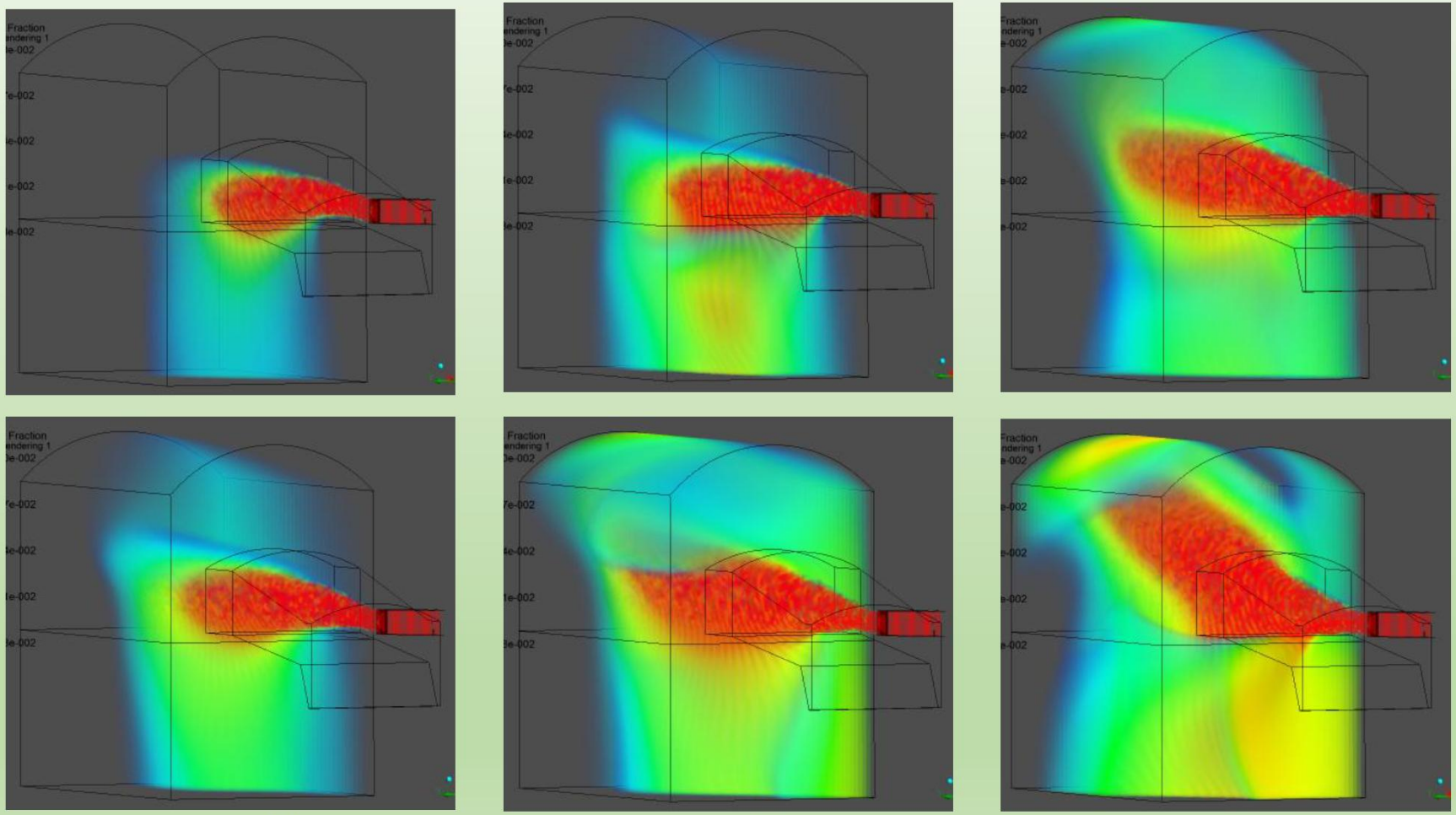
Investigation on the **air mass flow extracted** by the bypass at different operative condition of the auxiliary air injectors.



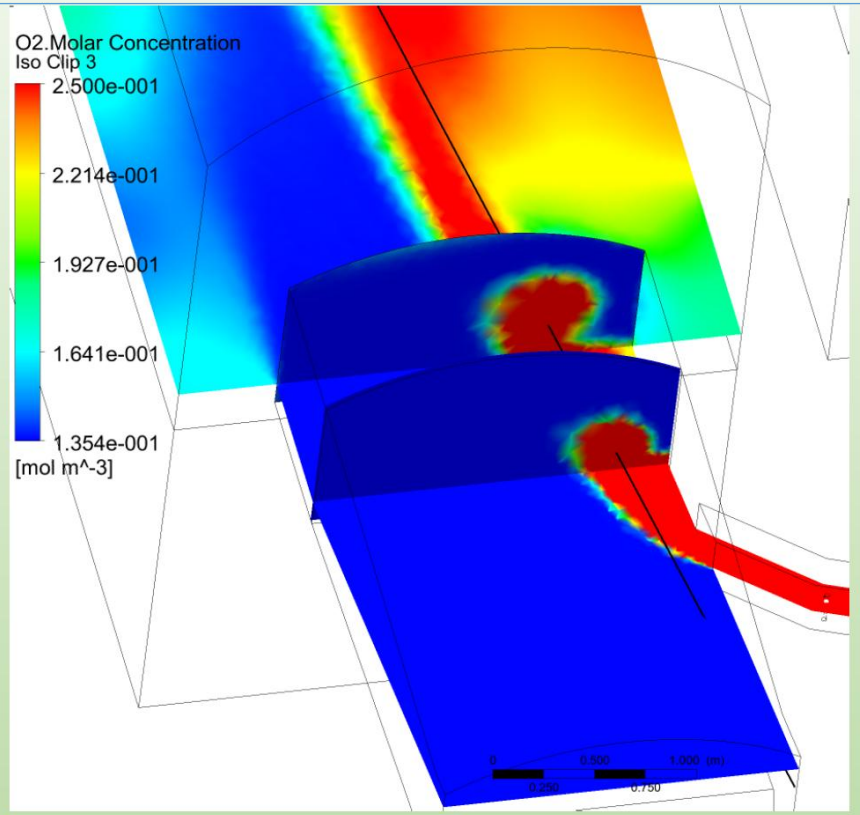


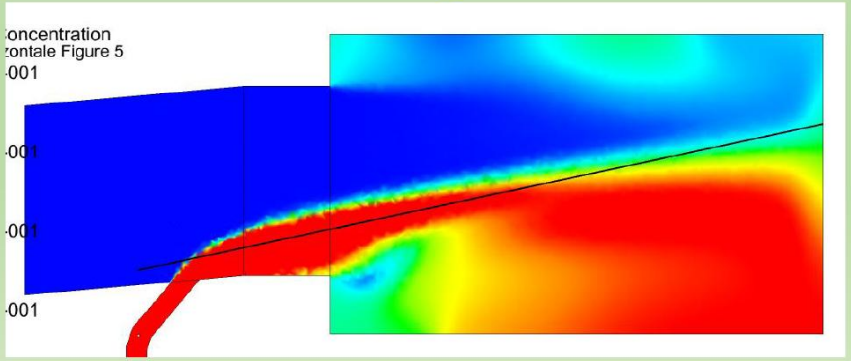


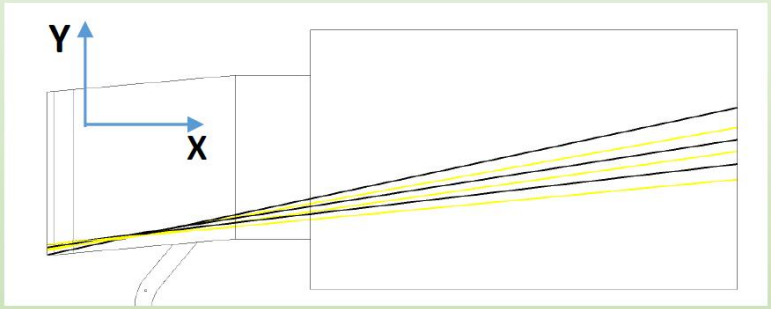
Air Staging jet at different operative condition of the auxiliary air injectors.

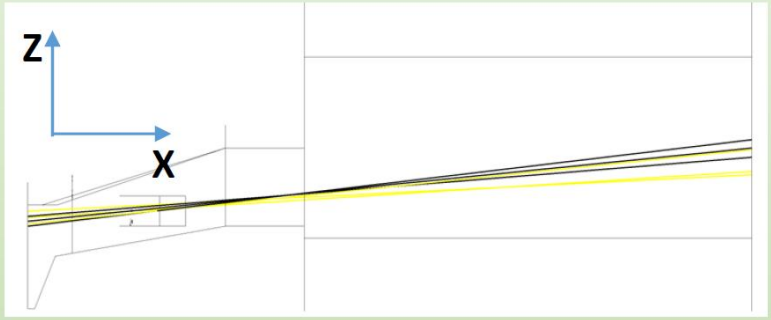


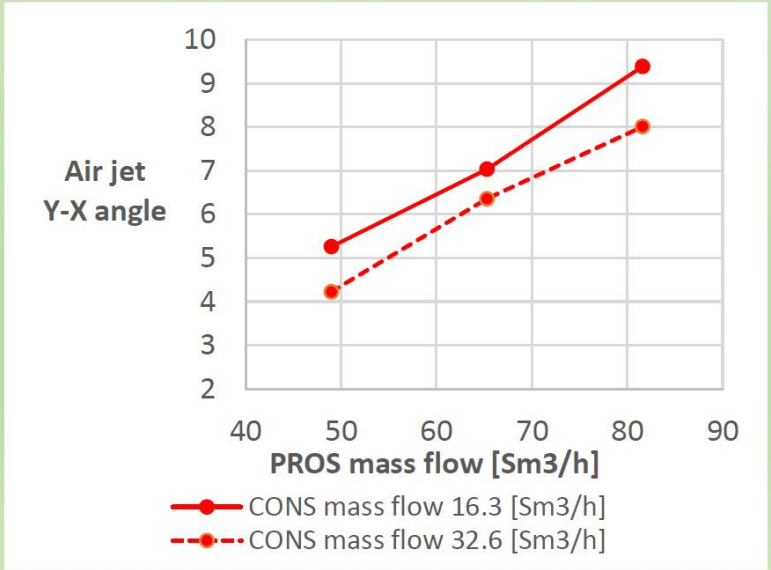
Bypass **jet direction** analysis at different operative condition of the auxiliary air injectors.

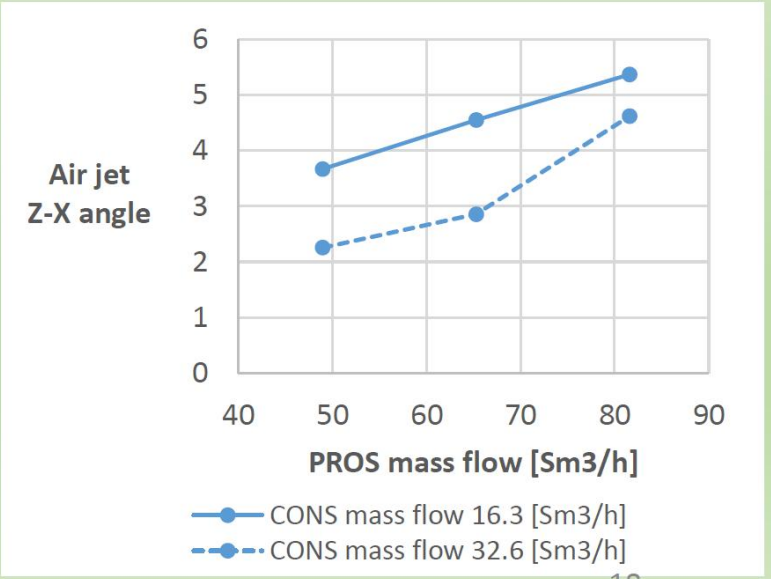




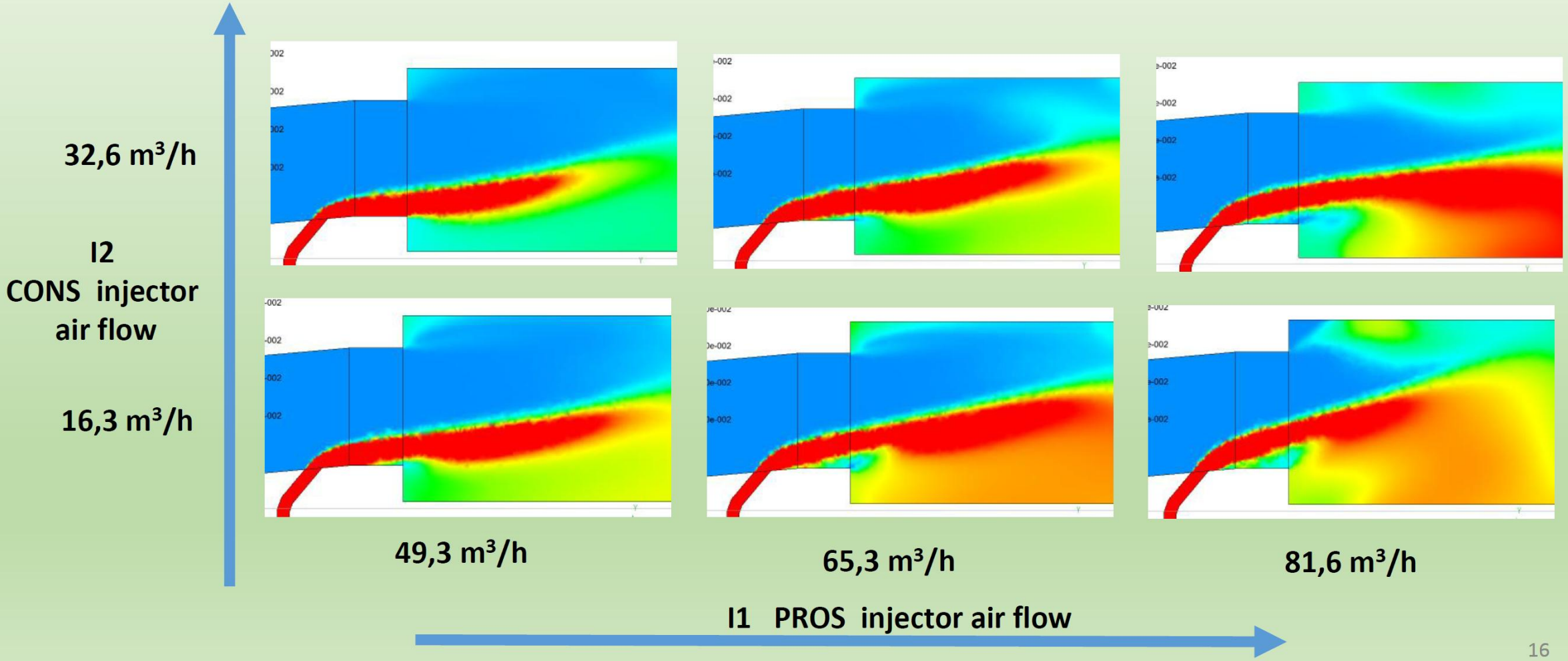








Air Staging jet at different operative condition of the auxiliary air injectors (TOP View)

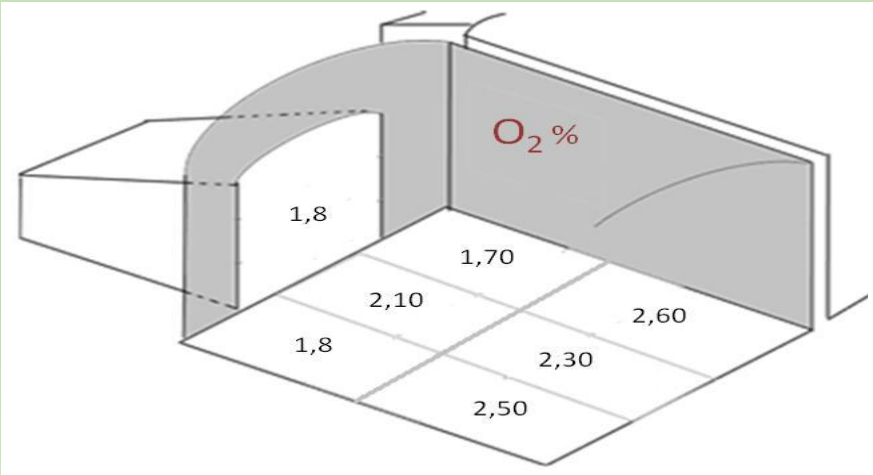


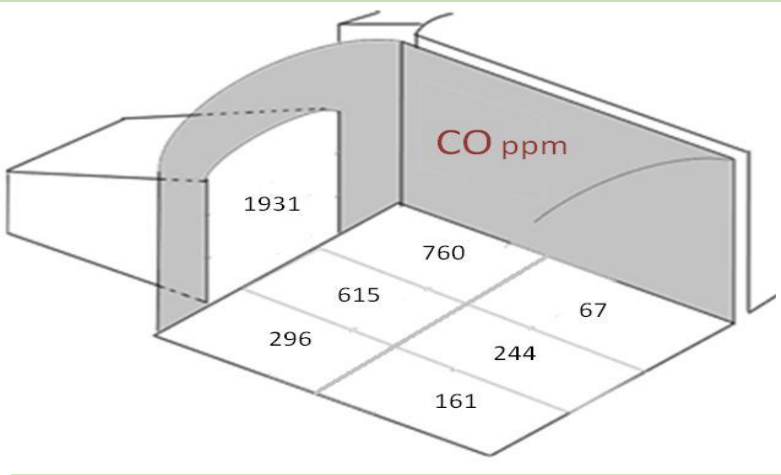
Baseline characterization - off gas analysis

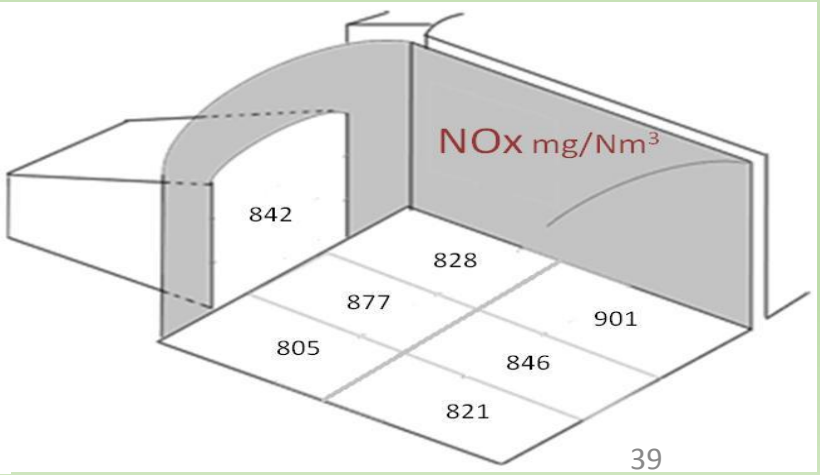
The waste gases produced by Altare (SV) furnace No. 2 with the Hybrid air staging system turned **off** were characterized to determine the reference state of combustion.

At the top of the regenerator chambers the flue gases stream was mapped just above the checkerworks in 6 different positions, following a 3 x 2 grid; in the port neck the probe was placed only in the central position. The results, averaged over several complete inversions, are reported below.

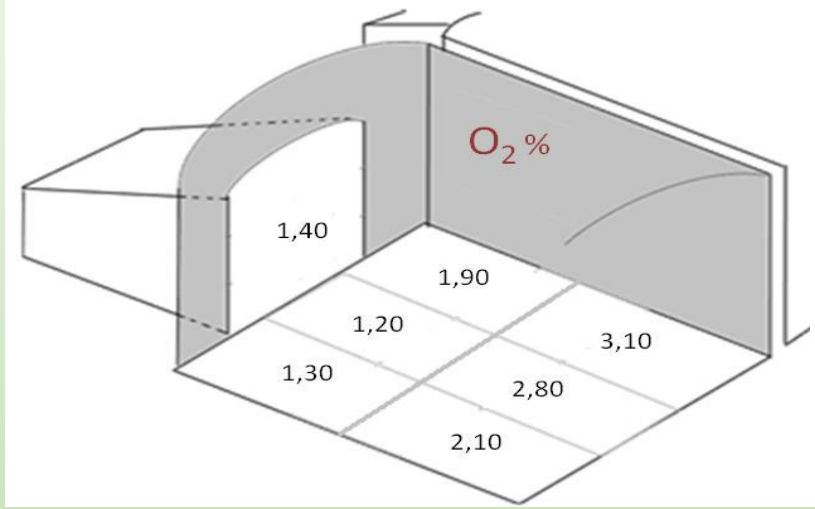
Hybrid air staging OFF – Flue gases Chamber

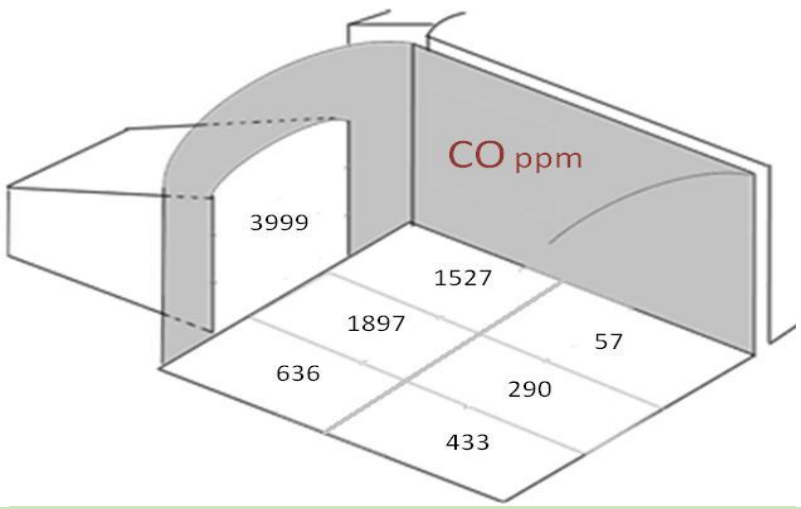


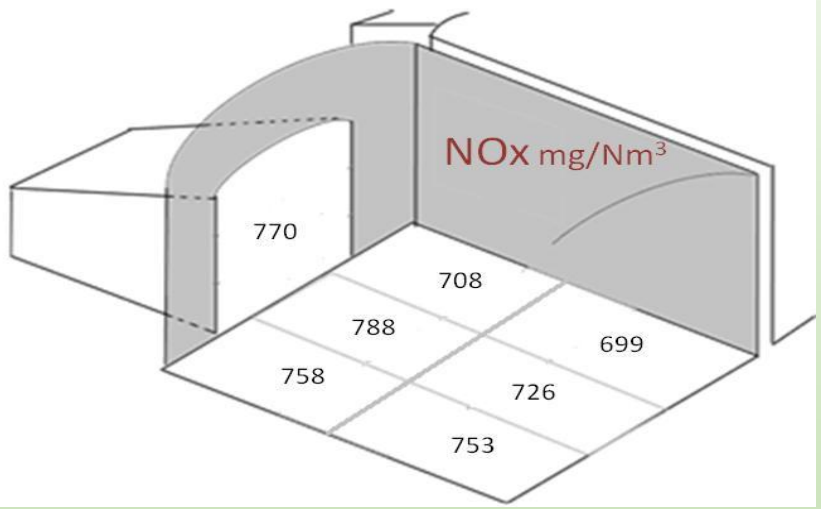




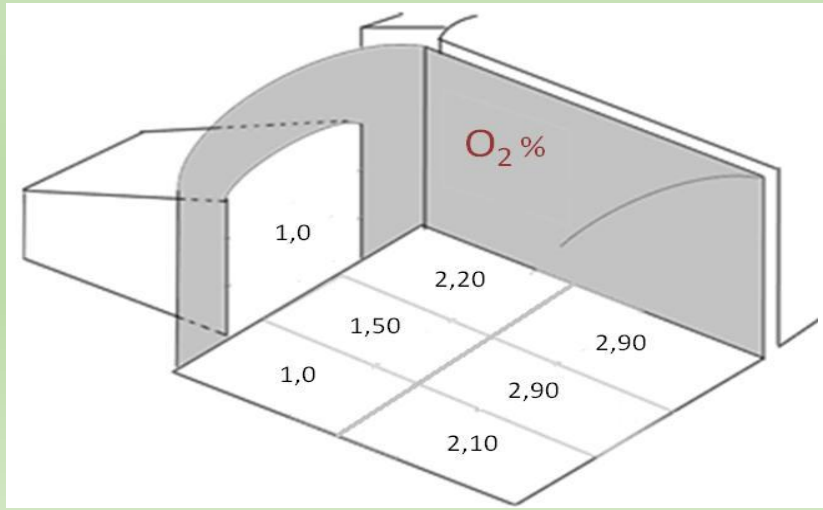
20 m³/h "cooling air" – 20 m³/h "propelling air" 1st condition

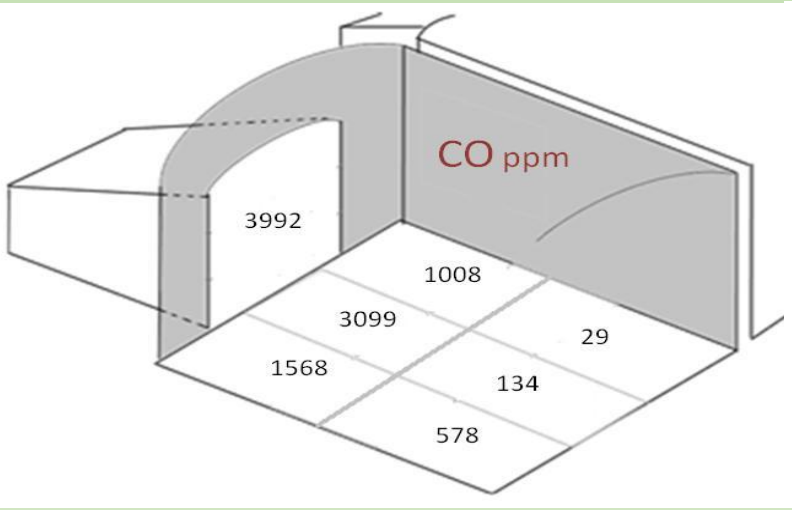


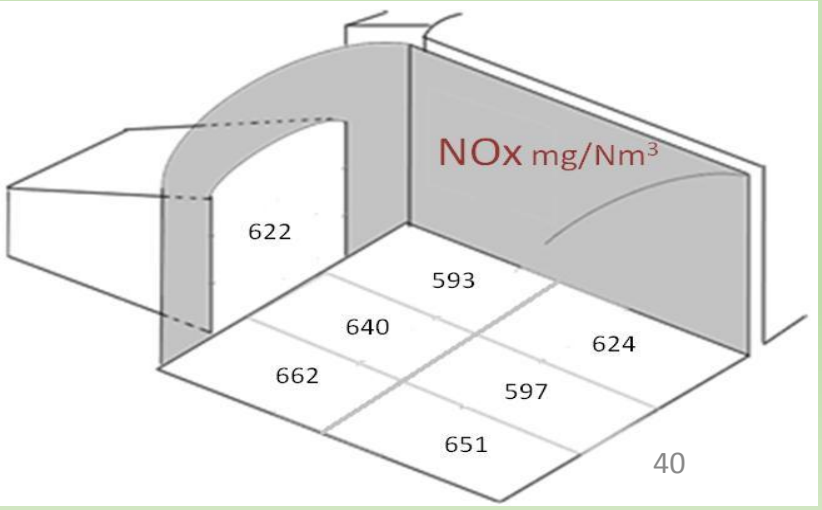




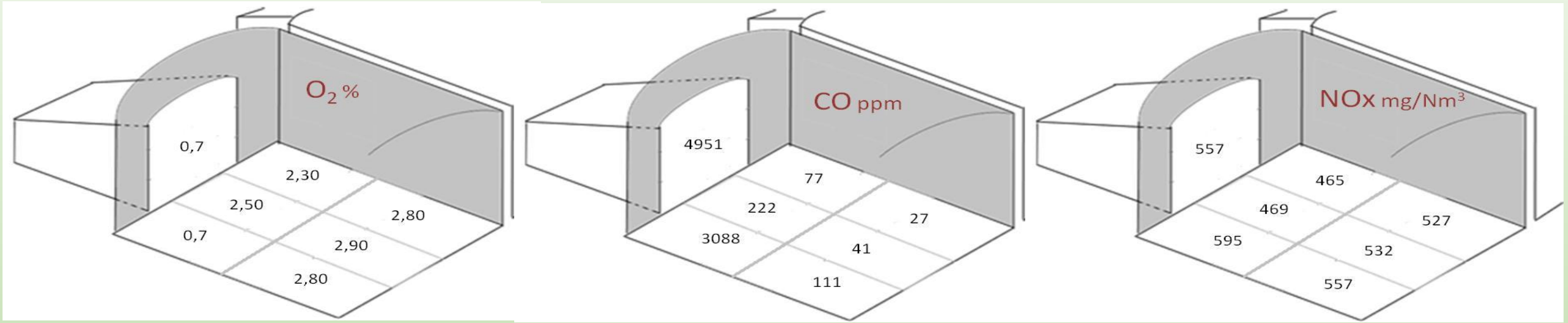
20 m³/h "cooling air" – 40 m³/h "propelling air" 2nd condition

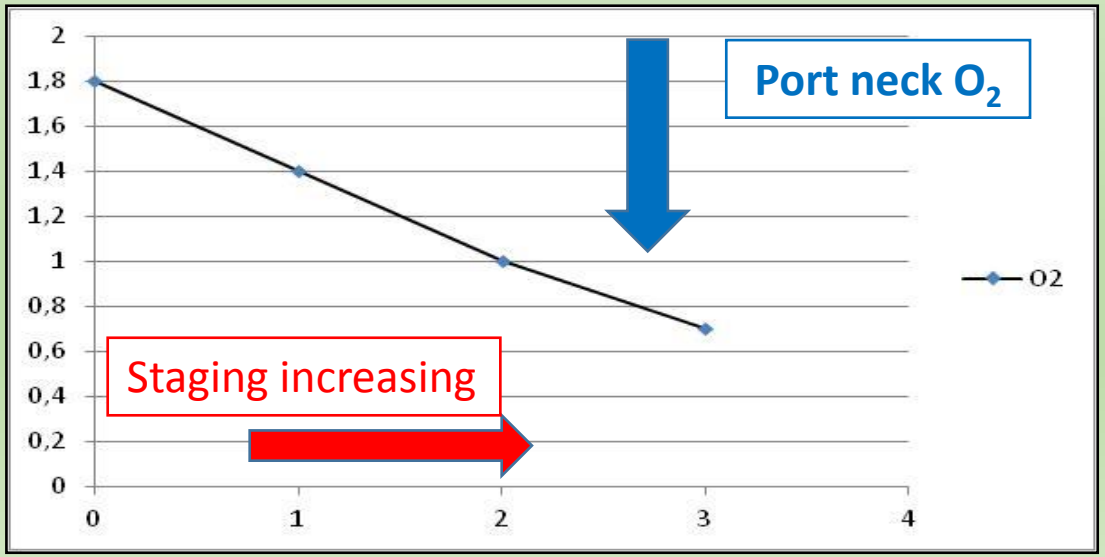


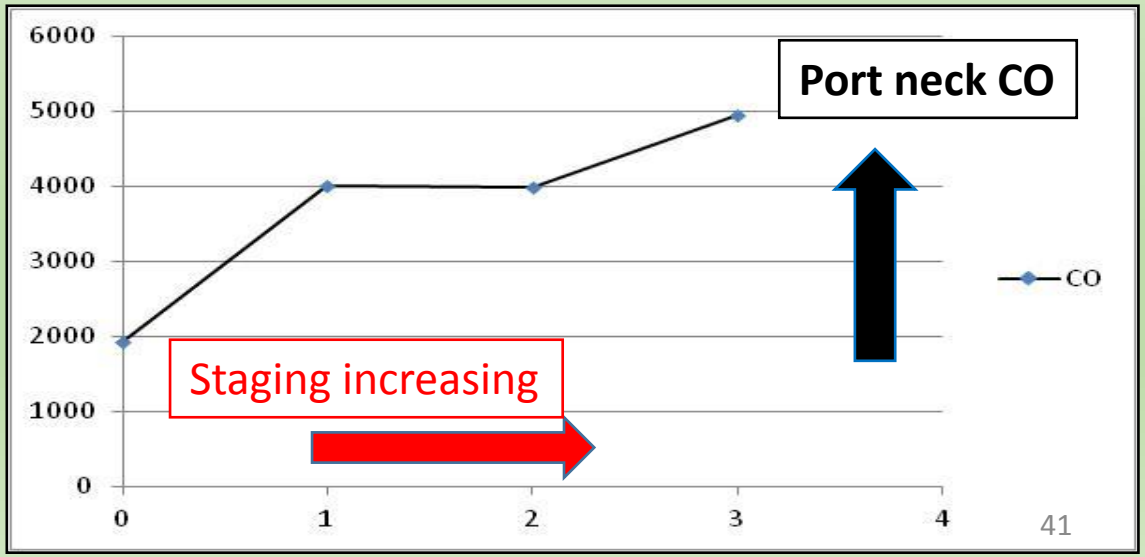


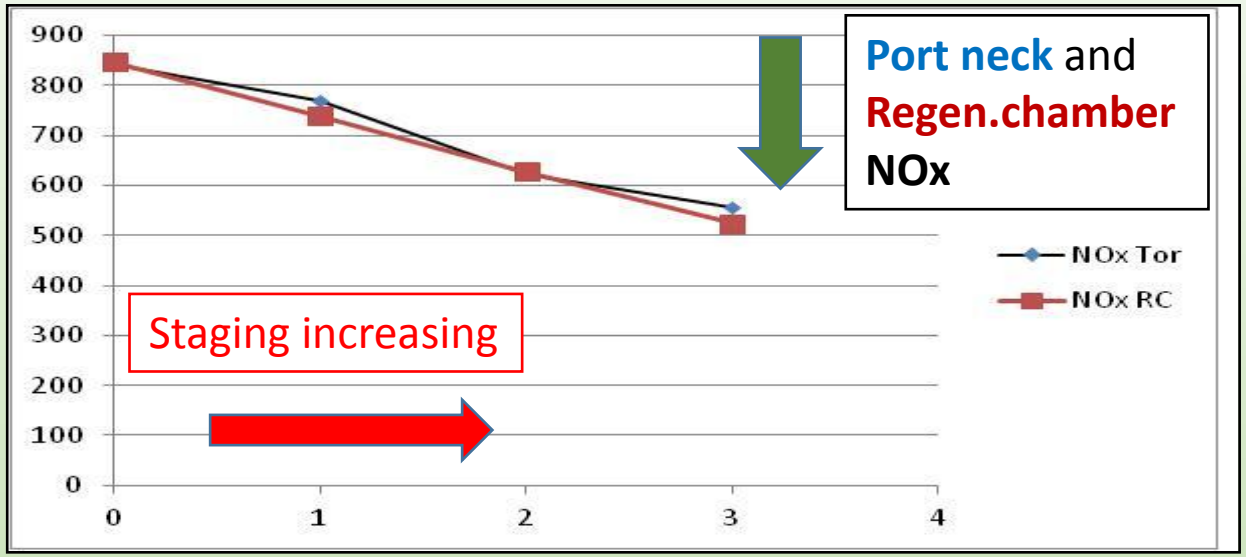


20 m³/h "cooling air" – 80 m³/h "propelling air" ***3rd condition***



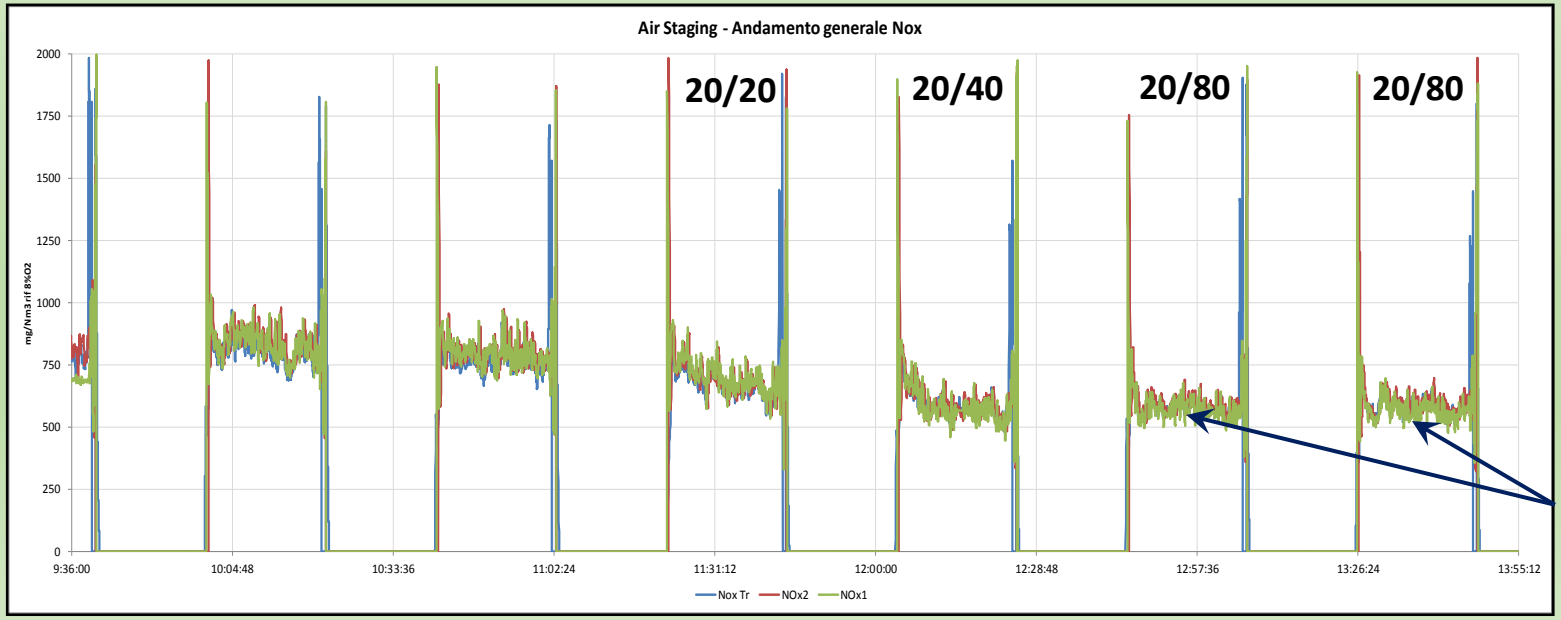






Port neck (TOR)					
setup	OFF	20/20	20/40	20/80	U.M.
O_2	1,8	1,4	1,0	0,7	%
NOx	842	770	622	557	mg/Nm³ %O_2
CO	1931	3999	3992	4951	ppm

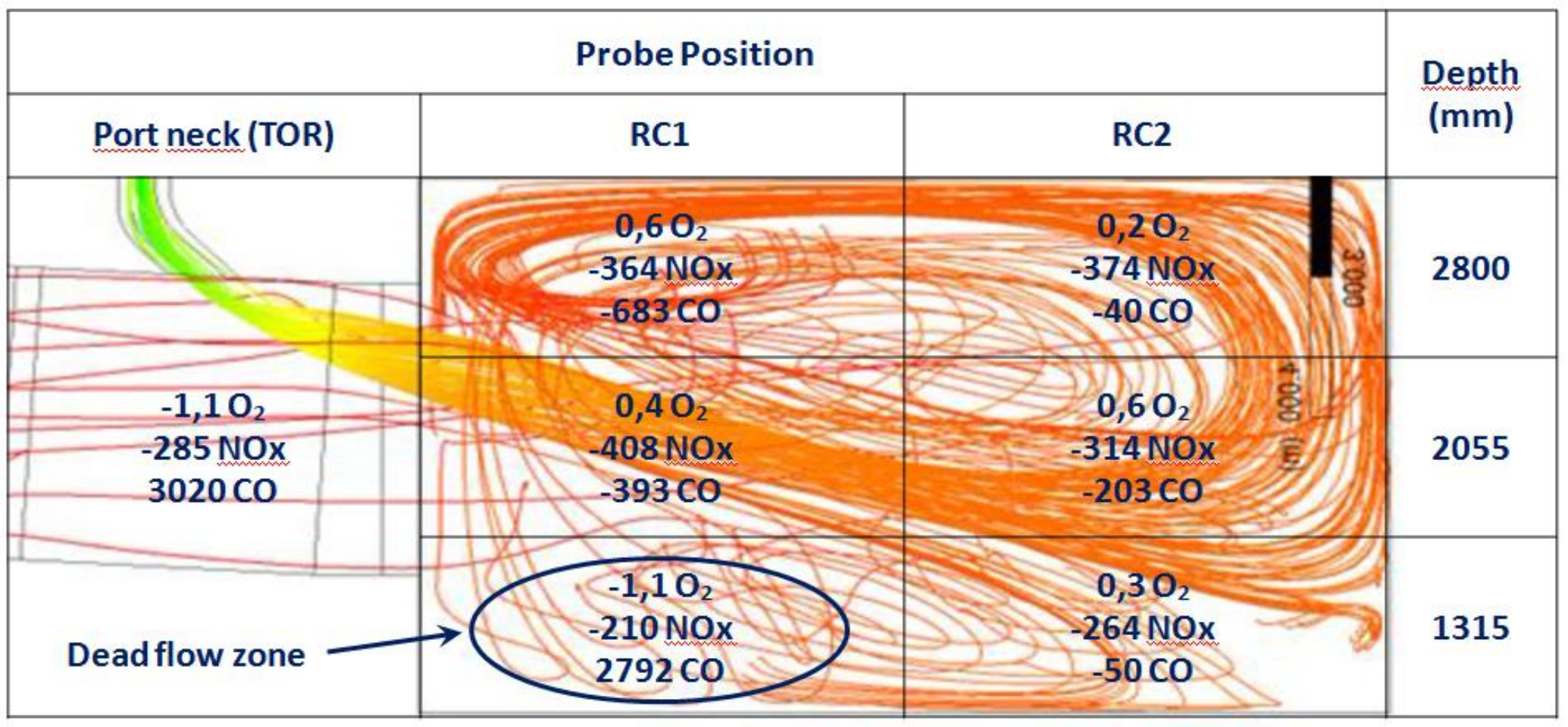
Regenerator Chamber (RC)					
setup	OFF	20/20	20/40	20/80	U.M.
O_2	2,17	2,07	2,10	2,33	%
NOx	846	739	628	524	mg/Nm³ %O_2
CO	357	807	1069	594	ppm



NOx percentage reduction VS baseline			
Air-staging	20/20	20/40	20/80
TOR	8,6	26,1	33,8
RC	12,6	25,1	38,1

Cooling flow [port neck in air phase] = 20 Nm³/h
Propelling Flow [port neck in fumes phase] = 80 Nm³/h

Below we report the results of the chemical mapping of flue gases in 20 / 80 Air Staging setup under the form of deltas with respect to baseline conditions (i.e. positive values = increase; negative values = decrease).



Summary of the NOx reduction performances of the PRIME Glass technologies

Primary measure	Plant monitored	NOx reduction rate	Energy Consumption (reference to baseline conditions)
Strategic Waste Gases Recirculation	Vetropack (ex Bormioli Rocco SpA) Trezzano (MI) Furnace n°3	10 - 30%	- 1.6% (WGR 10%) - 0.8% (WGR 20%) 0.3% (WGR 30%)
	Bormioli Rocco SpA Altare (SV) Furnace n°2		- 0.8% (WGR 10%) 0.0% (WGR 20%) + 1.0% (WGR 30%)
Cold air-staging	Vidrala Italia SpA Furnace n°4	10 - 30%	+ 1.5%
Hybrid Air Staging	Bormioli Rocco SpA Altare (SV) Furnace n°2	13 - 38%	+ 0.8% - 3,5% (reference to Cold Air Staging)

DATA ACQUISITION METHOD - MULTIPOINT CONTINUOUS MONITORING

This integrated approach allows the continuous and simultaneous monitoring of multiple parameters (composition, T, pressure, etc) of gaseous streams (air, flue gases) in several points of the furnace system.

1. Emissions chemical characterization

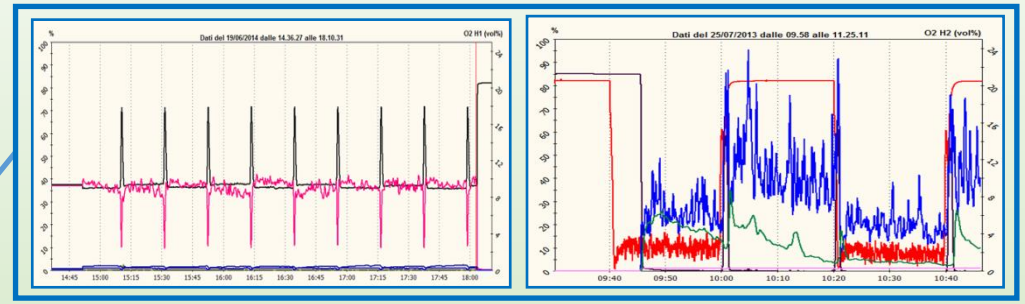
a. In the stack: emissions released into the atmosphere
b. In the port neck, at the top and bottom of the chambers
Waste gases and preheated combustion air

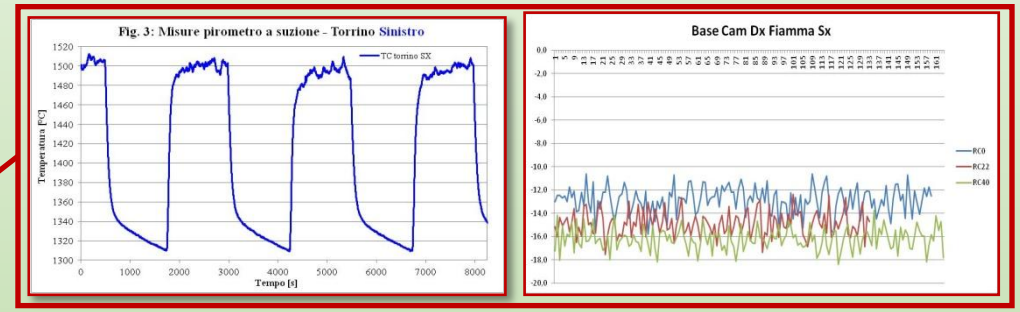
2. Temperatures and Pressures characterization

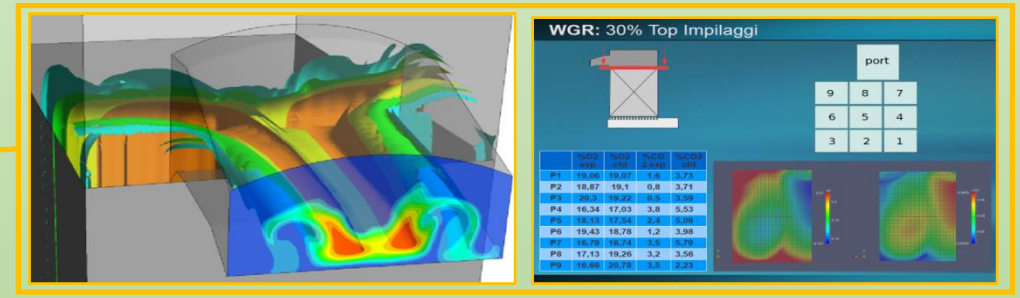
a. In the port neck, at the top and bottom of the chambers
Waste gases and preheated combustion air

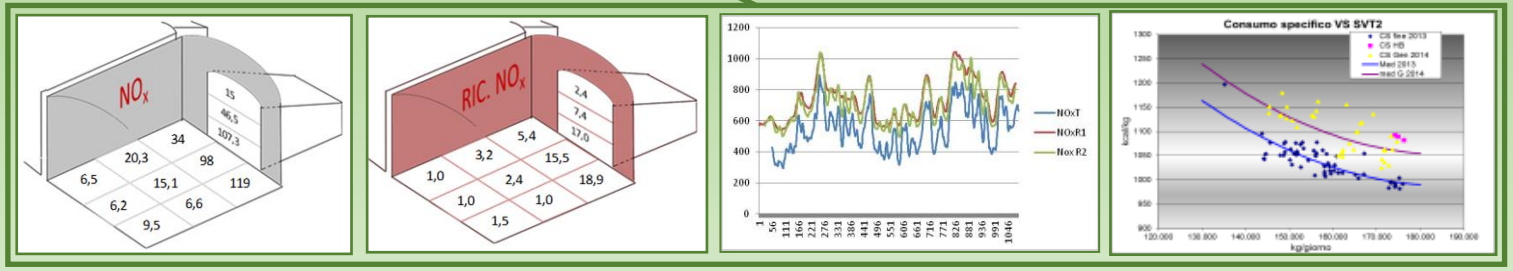
3. Energy, Fluid Dynamics and Chemical Reactions evaluations

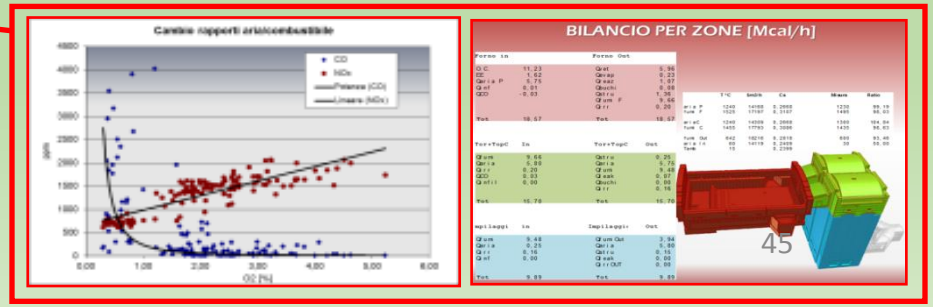
a. CFD simulations validation
b. Energy Balance assessment
c. Chemical reactions study











The **Multipoint Continuous Monitoring (MCM)** integrated experimental approach implemented by SSV has been instrumental for the development and final success of the PRIME Glass project, and has proven to be a powerful tool for the complete characterization of glass melting furnaces behaviour.

Through a dynamic, simultaneous and highly integrated analytical approach, it allows to obtain precious information such as:

- Flue gases and air **compositional and thermal mapping** (→ combustion optimization, CFD validation)
- Evaluation of **regenerator's efficiency and workload** distribution (→ system's "health" diagnostic)
- Quantification of energy flows throughout the system (→ **energy balance** assessment)
- Localization and quantification of **cold air infiltrations** and heat dispersions (→ efficiency improvement)
- Characteristic combustion behavior (→ **Smoke point** curves)

Visit www.primeglass.it

Prime Glass is co-financed by the European Union's Financial Instrument LIFE under n° LIFE12 ENV/IT/001020

Thank You for Your Attention !

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