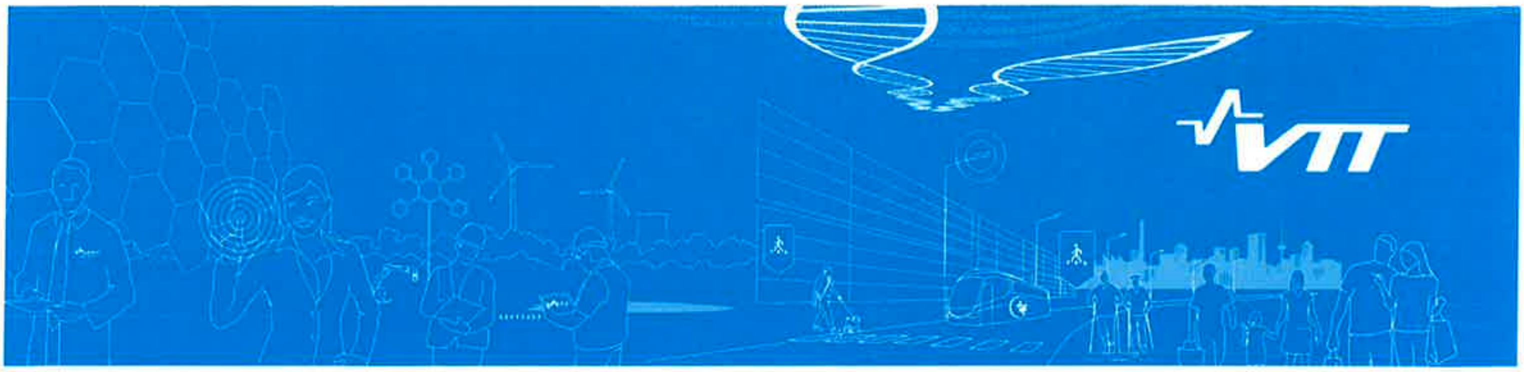
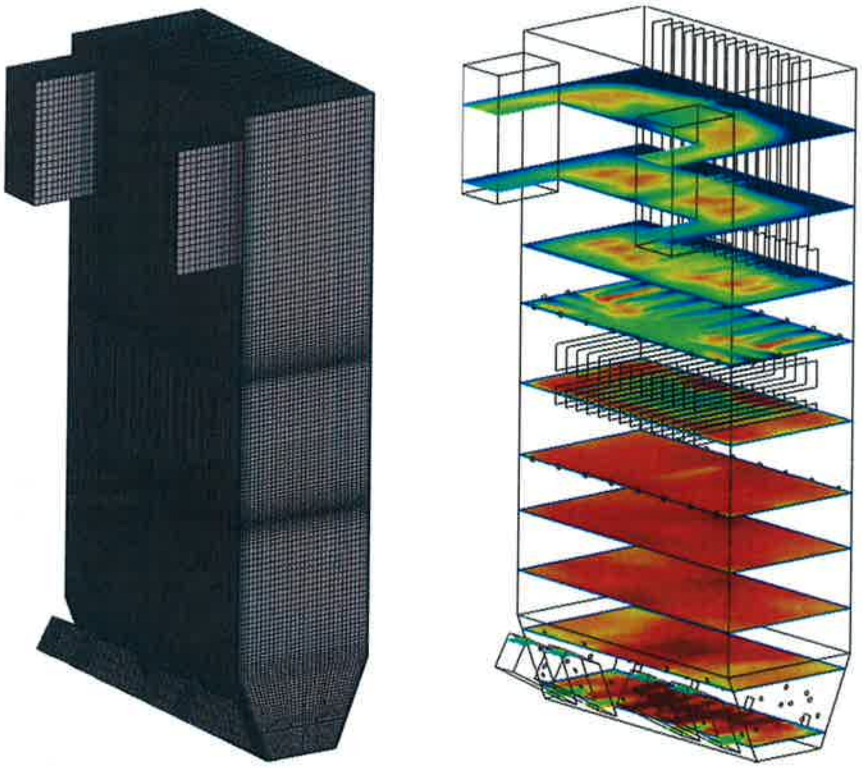


RESEARCH REPORT

VTT-R-03896-15



CFD simulations of air and oxy-fuel firing with several fuels in a large scale CFB furnace

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Confidentiality: Confidential

Report's title

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Summary

In the present study VTT's steady-state modelling approach for circulating fluidized beds was applied to simulate air and oxy-fuel firing with different fuels, lignite, coal and biomass, in a large scale CFB furnace. The over fire air (OFA) concept developed earlier by Fortum and VTT was applied in all cases but one. The normal operating mode without the OFA was simulated for reference. In air firing flue gas volumetric flow rates varied remarkably depending on the fuel, but in oxy-fuel firing they were more similar due to the modified feed gas O_2 content.

According to the results the OFA concept efficiently reduces NOx emission in air firing of lignite. At the same time solids circulation decreases, the furnace heat transfer declines moderately, the lower furnace temperature increases and the unburned carbon remains at the original level. CO burnout is predicted to be a bit weaker in the OFA case.

In air firing of different fuels with OFA heat transfer and the furnace temperature are simulated to increase and solids circulation to decrease along with improving fuel quality. The UBC flow and the exit CO concentration are predicted to be higher with biomass and lignite and lower with coal and the coal/biomass mixture. The simulated NOx and N_2O emission are small with all fuel types thanks to the efficient staging.

In oxy-fuel firing the furnace performance is more similar with different fuels due to the fuel dependent feed gas O_2 concentration. The upper furnace temperatures are lower in oxy-fuel cases as a consequence of rise in flue gas heat capacity. Solids circulation and the UBC flow are reduced in cases with increased feed gas O_2. The predicted CO emissions are comparable to air firing. The exit NO, HCN, NH_3 and especially N_2O concentrations increase in connection with flue gas recirculation. With coal the decreased furnace temperature also favours N_2O formation over NO.

Confidentiality	Confidential

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Contents

1. Introduction

Reduction of CO_2 emissions plays a major role in the efforts to combat climate change. CLEEN - Carbon Capture and Storage Program (CCSP), inside which the results presented in the report were produced, searches improved methods for capturing carbon in power plants and storing it permanently. Oxy-fired circulating fluidized bed (CFB) boilers are one approach towards these goals.

The specific target of the present study was to evaluate the performance of a utility scale CFB boiler furnace under air and oxy-fuel combustion conditions with several fuel types. Lignite, hard coal, biomass and a mixture of coal and biomass were considered.

2. Methods

The steady-state modeling approach applied in this work was developed at VTT for simulation of large circulating fluidized beds. It is based on time-averaged Eulerian-Eulerian equations for gas-solid hydrodynamics. The time-averaged continuity and momentum equations were developed in Taivassalo et al. 2012 by averaging the corresponding time-dependent equations over time and by deriving closure relations on the basis of averaged transient simulation results.

The methods and models have been validated by simulations of the 12 MW_{th} Chalmers CFB boiler in Gothenburg, Sweden (Taivassalo et al., 2012) and of a 135 MWe CFB boiler in Ruzhou, China (Peltola et al., 2013). Comparisons between simulation results and measured values proved that the models predict correctly the typical flow pattern in a CFB, with a dense bottom region and down-flow at walls and vertical heat exchanger surfaces. Simulated vertical pressure profiles matched well their measured counterparts. This indicates that the distribution of the bed mass along the riser height is correctly predicted. Distributions of gas components were well predicted in the simulation of Chalmers boiler but in the case of the larger Ruzhou boiler differences between measured and predicted oxygen concentrations were observed. However, in general the results represent the reality inside the furnace reasonably well. Thus the simulation tool can be considered suitable for the present analysis, which should be considered more of qualitative than of quantitative nature, i.e. the predicted values are not necessarily quantitatively accurate presentations of the reality although the direction and order of magnitude of the studied effects should be correctly predicted.

The simulations are carried out with a set of models implemented into the Openfoam® software platform.

3. The simulated CFB boiler and the studied conditions

3.1 Furnace geometry

The purpose of the study was to simulate oxy-fuel combustion in a typical industrial CFB boiler furnace. For that purpose, the geometry and case description were set as close as possible to conditions in a commercial CFB boiler. The largest amount of detailed information on boiler geometry and operational parameters was publicly available for one of the CFB boilers in Turow, Poland, and thus that boiler served as a base for the modeled furnace. The description of the Turow boiler given in the literature is simplified and e.g. locations of startup burners and air flows through them are not available. Thus the simulated boiler doesn't to all small details match the real Turow boiler. However, the essential geometrical description is correct enough for the present study. The geometry was defined according to the data given in Korhonen, 2001. The cross-section of the furnace is 21 m by 10 m and the height 44 m. The refractory lined bottom section is narrower. The boiler is equipped with two cyclones.

The separated solids return to furnace bottom through four return ducts. Solid fuel is fed through four feeders at the front wall and trough the four return ducts as well. Secondary air is according to Korhonen (2001) fed into the Turow CFB through orifices at all four walls in the conical bottom section. In the upper part of the riser there are wing wall superheaters and in the middle section superheaters of omega type. In the simulations the two stage combustion system designed earlier by Fortum and VTT in co-operation was considered. The related over fire air (OFA) nozzles are located above the omega type superheaters. The geometry and the computational mesh used in the simulations are shown in Fig. 1.

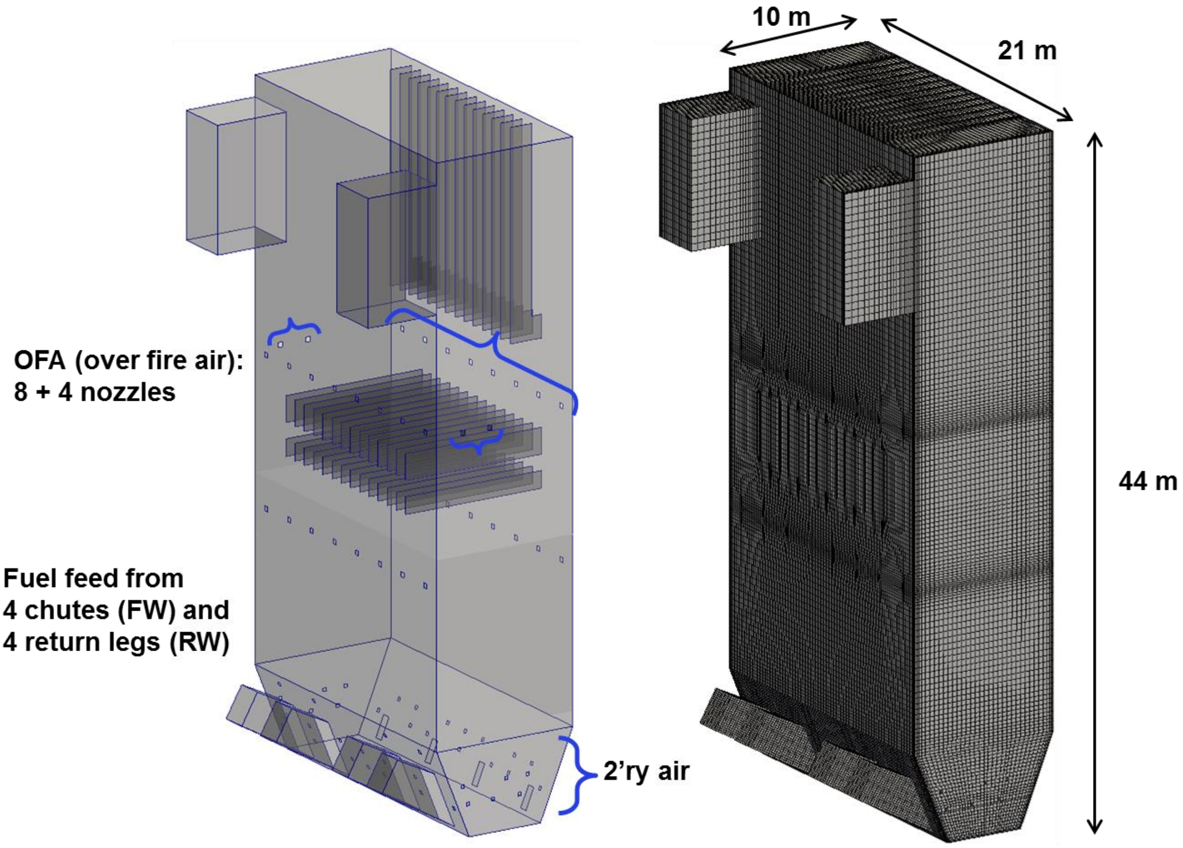


Figure 1. Furnace geometry and the computational mesh

3.2 The fuels

The actual fuel in the Turow boiler is Polish lignite. Ultimate and proximate analysis data, the particle size distribution and heating values were taken from Krzywanski et al. (2010). The other fuels considered in the study are those typically fired in Finnish boiler furnaces in general. They are a Russian hard coal (Kirkyaskaya) and Finnish forest residue as the biomass fuel. The coal analysis was taken from Savolainen (2005) and the analysis of forest residue from Alakangas (2000). Particle size distributions were estimated based on general data for CFB (coal) and BFB (forest residue) boilers. Additionally primary fragmentation and the non-spherical shape of biomass particles were taken into account in deriving the final distributions. Fuel properties are shown in table 1 and particle size distributions in figure 2.

Compared to the other fuels lignite is especially characterized by small particle size and high ash content, coal by low moisture content and high heating value and forest residue by large particle size, high volatile content and low ash content. These differences greatly affect the boiler operation as fuel flow rate, air demand and flue gas flow rate as well as combustion and emission behavior change depending on the fuel utilized.

Table 1. Fuel properties.

Lignite (Polish)	
Moisture [w-%]	43.5
Ultimate analysis [w-%], dry	
C	49.6
H	5.0
O	15.1
N	0.7
S	0.6
ash	29.0
Proximate analysis [w-%], dry	
volatiles	35.2
fixed C	34.5
ash + N + S	30.3
LHV [MJ/kg], wet	10.60
LHV [MJ/kg], dry	20.65

Coal (Russian, Kirkyaskaya)	
Moisture [w-%]	10.7
Ultimate analysis [w-%], dry	
C	73.5
H	5.0
O	7.2
N	2.4
S	0.6
ash	11.3
Proximate analysis [w-%], dry	
volatiles	36.4
fixed C	49.3
ash + N + S	14.3
LHV [MJ/kg], wet	25.34
LHV [MJ/kg], dry	28.70

Forest residue (Finnish)	
Moisture [w-%]	50.0
Ultimate analysis [w-%], dry	
C	50.0
H	6.1
O	41.6
N	0.3
S	0.01
ash	2.0
Proximate analysis [w-%], dry	
volatiles	80.0
fixed C	17.7
ash + N + S	2.3
LHV [MJ/kg], wet	8.40
LHV [MJ/kg], dry	19.25

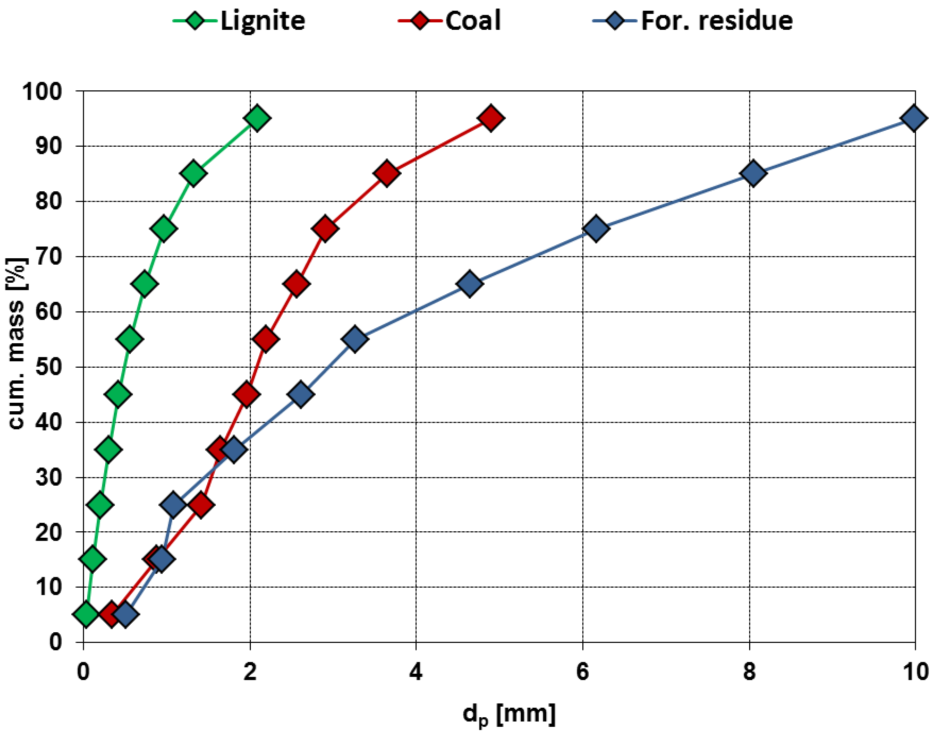


Figure 2. Cumulative distributions of fuel particle diameter used in simulations.

3.3 Simulated cases

Altogether nine different simulations were carried out with four different fuel types: pure lignite, pure coal, pure forest residue and a fuel mixture consisting of 50 % coal and 50% forest residue based on energy input. The boiler full load was considered in all cases and the capacity (670 MW_{fuel}) was assumed to remain unchanged independent of the fuel. Both air and oxy-fuel fired cases were simulated for each fuel. Additionally the normal operation of the Turow furnace, that is air firing of lignite without the over fire air concept, was simulated for reference. In oxy-fuel combustion the O_2 concentration of the feed gas was varied such that it was 24 vol-% for lignite, 21 vol-% for coal, 26 vol-% for forest residue and again 24 vol-% in co-firing. Thus oxygen concentration increases along with decreasing heating value of the fuel. Wet flue gas recirculation was presumed. The total stoichiometry was held constant in all cases and the air or feed gas was distributed between primary (fluidization), secondary and OFA feeds with the shares of 60, 17 and 23 % respectively (or 60, 40 and 0 % in the reference case). Case input values are listed in tables 2 & 3.

Table 2. Case numbering and input values: lignite & coal

	Lignite firing			**Coal firing**	
	Case 0	**Case 1**	**Case 2**	**Case 3**	**Case 4**
	air, ref.	air	oxy 24% O2	air	oxy 21% O2
Fuel input [MW]	670	670	670	670	670
Fuel flow rate [kg/s]	63.2	63.2	63.2	26.4	26.4
Comb. gas flow rate [kg/s]	281	281	244.8	269.9	321.7
Comb. gas flow rate [m3n/s]	218.3	218.3	190.2	209.7	208.9
Comb. gas distribution [%]: 1ry/2ry/OFA	60/40/0	60/17/23	60/17/23	60/17/23	60/17/23
Comb. gas composition [vol-%]: O2/N2/H2O/CO2	21/79/0/0	21/79/0/0	24/0/47.2/28.8	21/79/0/0	21/0/26.8/52.2
Flue gas O2 [vol-%], dry / wet	3.0 / 2.4	3.0 / 2.4	6.8 / 2.7	3.0 / 2.8	3.0 / 2.8
Flue gas flow rate [kg/s]	333.3	333.3	297.2	293	344.7
Flue gas flow rate [m3n/s]	266.3	266.3	238.2	221	220.1
Flue gas composition [vol-%] O2/N2/H2O/CO2	2.4/64.8/20.4/12.4	2.4/64.8/20.4/12.4	2.7/0.0/60.5/36.8	2.8/75.1/7.5/14.6	2.8/0.0/33.0/64.2
Flue gas recirculation [%]	0	0	62	0	77

Table 3. Case numbering and input values: forest residue & co-firing

	Biomass firing		**Co-firing: coal + biomass**	
	Case 5	**Case 6**	**Case 7**	**Case 8**
	air	oxy 26% O2	air	oxy 24% O2
Fuel input [MW]	670	670	335 + 335	335 + 335
Fuel flow rate [kg/s]	79.7	79.7	13.2 + 39.9	13.2 + 39.9
Comb. gas flow rate [kg/s]	279.8	218	274.8	247.5
Comb. gas flow rate [m3n/s]	217.4	174.9	213.5	186.1
Comb. gas distribution [%]: 1ry/2ry/OFA	60/17/23	60/17/23	60/17/23	60/17/23
Comb. gas composition [vol-%]: O2/N2/H2O/CO2	21/79/0/0	26/0/49.8/24.2	21/79/0/0	24/0/43.5/32.5
Flue gas O2 [vol-%], dry / wet	3.0 / 2.2	7.4 / 2.6	3.0 / 2.4	6.2 / 2.7
Flue gas flow rate [kg/s]	358.6	296.8	325.7	298.5
Flue gas flow rate [m3n/s]	292.1	249.6	256.5	229.1
Flue gas composition [vol-%] O2/N2/H2O/CO2	2.2/58.9/26.2/14.6	2.6/0.0/65.6/31.8	2.4/65.8/18.2/13.6	2.7/0.0/55.7/41.6
Flue gas recirculation [%]	0	53	0	63

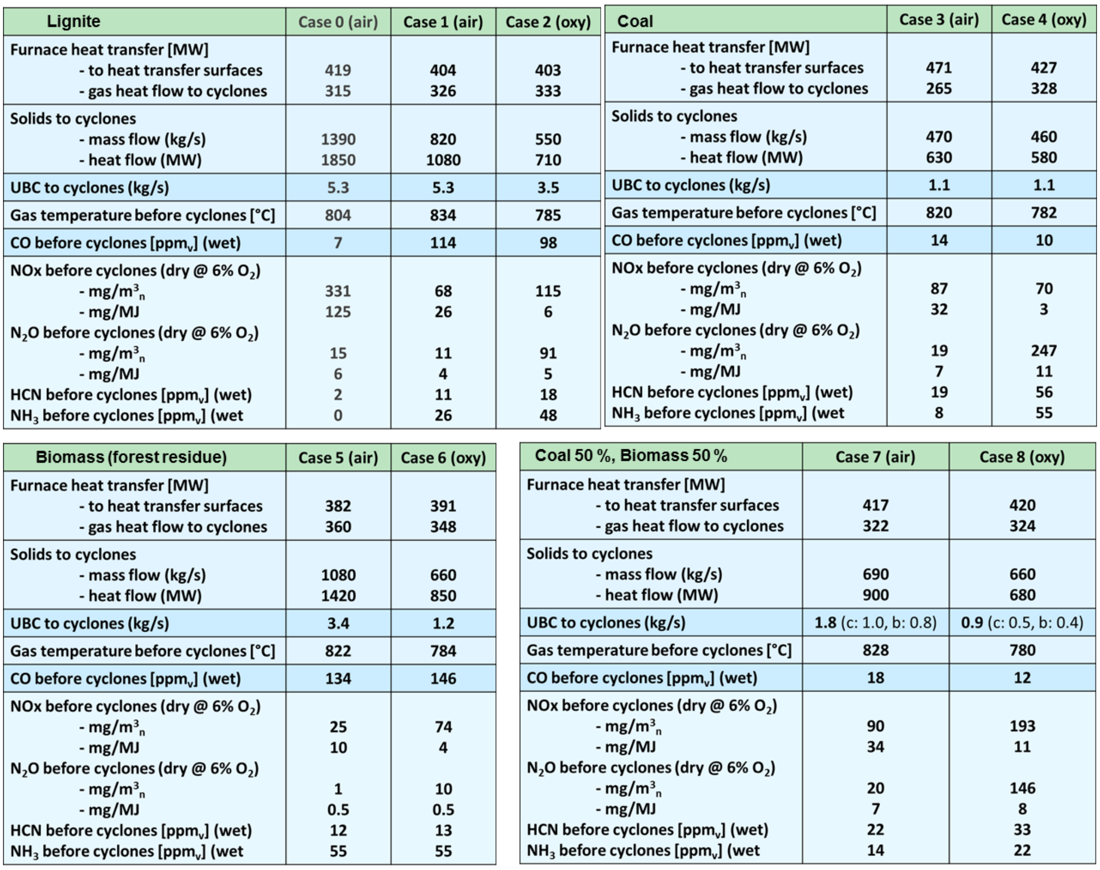
Due to a higher heating value, the mass flow rate of coal is notably smaller than the flow rates of other fuels. In air firing the flue gas (normalized, volumetric) flow rate with coal is small whereas in the case of biomass the flue gas flow rate is some 30 % greater in comparison. Lignite and the mixture of coal and biomass lie between those extremes. This means that fluidization and freeboard velocities will change depending on the fuel type and, of course, gas temperature and density have an effect too. The air demand does not vary that much. It lies inside ± 10 % margin with all the fuel types considered.

The picture is a bit different in oxyfuel combustion as feed gas O_2 concentration is modified depending on the fuel quality. The flue gas flow rates (normalized, volumetric) decrease compared to air firing as feed gas O_2 concentration is above 21 vol-% with all fuels except coal. All oxyfuel cases studied lie inside ± 15 % margin in this perspective. The corresponding mass flow rates are even closer to one another, excluding coal. In the coal case the flue gas CO_2 content is high contributing to greater mass flow. With other fuels water vapor dominates in the flue gas presuming wet recirculation. In the biomass case the flue gas H_2O content is as high as 66 vol-%. The recirculation ratio depends on the feed gas O_2 content being greater with low O_2. In cases studied the recirculation ratio varies between 53 and 77 %. The feed gas volumetric flow rates decrease remarkably compared to air firing due to changes in O_2 concentration. All in all the fluidization and freeboard velocities may be affected by adjusting the feed gas O_2 concentration, but this will certainly affect the combustion characteristics in the furnace as well.

4. Results

Summary of the numerical results are presented in table 4. Graphical information of certain key quantities is shown in figures 3 – 14 in form contour plots taken from several vertical cross sections in the furnace for each case.

Table 4. Summary of the numerical values applied in the simulations



Lignite	Case 0 (air)	Case 1 (air)	Case 2 (oxy)
Furnace heat transfer [MW]			
- to heat transfer surfaces	419	404	403
- gas heat flow to cyclones	315	326	333
Solids to cyclones			
- mass flow (kg/s)	1390	820	550
- heat flow (MW)	1850	1080	710
UBC to cyclones (kg/s)	5.3	5.3	3.5
Gas temperature before cyclones [°C]	804	834	785
CO before cyclones [ppm_v] (wet)	7	114	98
NOx before cyclones (dry @ 6% O_2)			
- mg/m^3_n	331	68	115
- mg/MJ	125	26	6
N_2O before cyclones (dry @ 6% O_2)			
- mg/m^3_n	15	11	91
- mg/MJ	6	4	5
HCN before cyclones [ppm_v] (wet)	2	11	18
NH_3 before cyclones [ppm_v] (wet	0	26	48

Coal	Case 3 (air)	Case 4 (oxy)
Furnace heat transfer [MW]		
- to heat transfer surfaces	471	427
- gas heat flow to cyclones	265	328
Solids to cyclones		
- mass flow (kg/s)	470	460
- heat flow (MW)	630	580
UBC to cyclones (kg/s)	1.1	1.1
Gas temperature before cyclones [°C]	820	782
CO before cyclones [ppm_v] (wet)	14	10
NOx before cyclones (dry @ 6% O_2)		
- mg/m^3_n	87	70
- mg/MJ	32	3
N_2O before cyclones (dry @ 6% O_2)		
- mg/m^3_n	19	247
- mg/MJ	7	11
HCN before cyclones [ppm_v] (wet)	19	56
NH_3 before cyclones [ppm_v] (wet	8	55

Biomass (forest residue)	Case 5 (air)	Case 6 (oxy)
Furnace heat transfer [MW]		
- to heat transfer surfaces	382	391
- gas heat flow to cyclones	360	348
Solids to cyclones		
- mass flow (kg/s)	1080	660
- heat flow (MW)	1420	850
UBC to cyclones (kg/s)	3.4	1.2
Gas temperature before cyclones [°C]	822	784
CO before cyclones [ppm_v] (wet)	134	146
NOx before cyclones (dry @ 6% O_2)		
- mg/m^3_n	25	74
- mg/MJ	10	4
N_2O before cyclones (dry @ 6% O_2)		
- mg/m^3_n	1	10
- mg/MJ	0.5	0.5
HCN before cyclones [ppm_v] (wet)	12	13
NH_3 before cyclones [ppm_v] (wet	55	55

Coal 50 %, Biomass 50 %	Case 7 (air)	Case 8 (oxy)
Furnace heat transfer [MW]		
- to heat transfer surfaces	417	420
- gas heat flow to cyclones	322	324
Solids to cyclones		
- mass flow (kg/s)	690	660
- heat flow (MW)	900	680
UBC to cyclones (kg/s)	**1.8** (c: 1.0, b: 0.8)	**0.9** (c: 0.5, b: 0.4)
Gas temperature before cyclones [°C]	828	780
CO before cyclones [ppm_v] (wet)	18	12
NOx before cyclones (dry @ 6% O_2)		
- mg/m^3_n	90	193
- mg/MJ	34	11
N_2O before cyclones (dry @ 6% O_2)		
- mg/m^3_n	20	146
- mg/MJ	7	8
HCN before cyclones [ppm_v] (wet)	22	33
NH_3 before cyclones [ppm_v] (wet	14	22

In the following the main observations are shortly pointed out.

4.1 The effect of air staging in air firing of lignite (Case 0 vs. Case1)

- According to the results the secondary air does not seem to mix very well with the unburned fuel in the furnace neither with nor without OFA. See figure 9.
- Staging with OFA…
  - Decreases fluidization velocity below the OFA level. In general the gas and solid velocity is more uniform across the cross-section in the lower part of the furnace in the staged mode of operation. Regions with high upward velocity that are a result of limited lateral penetration of the OFA air jets appear above the OFA elevation. See figures 5 & 6.
  - Leads to decrease in solids circulation. The solids are more concentrated in the lower part of the furnace. See figure 4 and table 1.
  - Slows down char combustion, but this is partly compensated by the reduced circulation such that the UBC (unburned carbon) to cyclones is not predicted to rise. The simulated CO to cyclones increases by contrast – however in reality, reactions still continue behind the outlet of the computational domain. See figures 7 – 10 and table 1.
  - Leads to a rise in temperature especially in the lower furnace as a consequence of more favourable stoichiometric conditions and decrease in solid phase vertical heat convection. The overall heat transfer to the furnace walls is predicted to decline moderately. The furnace exit gas temperature increases correspondingly. See figure 3.
  - Seems to be very effective in NOx reduction according to the results. Due to uncertainties related to emission modelling in CFBs at the moment the results are more qualitative than quantitative by nature. The predicted emission in the reference case is however well in line with the measured data from Turow boiler. In the staged case some of the NOx precursors (NH_3, HCN) leave the furnace unreacted as the consumption reactions are very slow in O_2 deficient conditions in the temperature range prevailing in CFB boilers.

4.2 Air firing of the three fuels

- Furnace temperature and heat transfer are predicted to increase remarkably along with the fuel heating value (forest residue: 380 MW → coal: 470 MW). With forest residue the residual flue gas heat content is highest emphasizing heat transfer in the convection section (and the cyclones) after the main furnace. The flue gas exit temperature is predicted to remain inside 15 °C margin with all fuels. See table 4 and figure 3.
- Solids circulation decreases with the flue gas flow. See table 4 and figure 4.
- The furnace flow pattern is rather similar in all OFA cases. Local differences exist. In the upper part the flow pattern is dominated by the OFA jets. See figures 5 & 6.
- The simulated UBC (unburned carbon) flow to the cyclones is remarkably low with coal due to the low flue gas flow combined with the high furnace temperature and large and dense particles that stay in the lower part of the furnace. Lignite particles are small, less dense and still contain remarkable amount of fixed C. They are more easily entrained by the gas flow producing the highest exit UBC in the simulations. Forest residue has a small fixed C content but the char particles are very light and

easily entrained. The combustion rate is also lower due to the low temperature level leading to a relatively large predicted exit UBC flow. In the co-firing case the heterogeneous combustion of biomass is supported by coal leading to a smaller UBC in comparison to pure biomass firing. See table 4 and figures 7 & 8.

- CO combustion follows similar trend as fixed C but is more affected by the upper furnace temperature. Burnout is rather good in all cases. See table 4 and figures 3 &10.

- NOx emission is predicted to be small in all cases thanks to the effective staging. The emission is highest in coal firing and co-firing mainly due to the high N content in the dry matter of coal. However coal char efficiently reduces NO via the heterogeneous reactions. In co-firing heterogeneous reduction is predicted to decline resulting in an emission level comparable to pure coal firing. Nitrous oxide formation remains small due to fuel characteristics (lignite & biomass), air staging and relatively high combustion temperature in the coal case. See table 4 and figures 11-14.

4.3 Oxy-fuel firing compared to air firing

- Oxy-fuel cases are characterized by 1) changes in fluidization and freeboard velocities, if feed gas O_2 concentration is different from air firing (lignite, forest residue, co-firing), 2) increased flue gas heat capacity due to high H_2O and CO_2 concentrations.

- Compared to air combustion: 1) Upper furnace temperatures go down with all fuels due to the flue gas heat capacity. 2) Lower furnace temperatures are similar or increase in cases with 24 % or 26 % O_2 in feed gas but decrease in the coal case (21 % O_2). 3) In-furnace heat transfer is enhanced with biomass (26 % O_2), remains similar with lignite and the fuel mixture (24 % O_2) and declines with coal (21 % O_2). See table 4 & figure 3.

- Because of the varied feed gas O_2 content differences in heat transfer between the fuels are smaller than in air combustion, especially the gap between coal and the other, low calorific fuels. See table 4.

- Solids circulation decreases along with increasing feed gas O_2 concentration compared to corresponding air firing cases. The UBC flow to cyclones follows the same trend and goes down in all cases but the one with coal. See table 4 and figures 4,7 & 8.

- The predicted CO emission is like in the corresponding air and oxy-fuel cases. See table 4 and figure 10.

- In general, oxy-fuel firing gives rise to the high simulated flue gas NO and N_2O concentrations due to recirculation of the species themselves and their precursors HCN & NH_3 with flue gas. The precursor concentrations increase in the similar manner. Particularly N_2O is very sensitive to this effect as it is not destroyed in the reactions occurring in the furnace to the same extent as NO. In case of coal the reduced temperature level contributes to the decrease in NO and the increase in N_2O concentrations in oxy-fuel firing. The specific emissions however decrease (except N_2O in coal and co-firing cases) as only part of the flue gas is lead out from the system. See table 4 and figures 11-14.

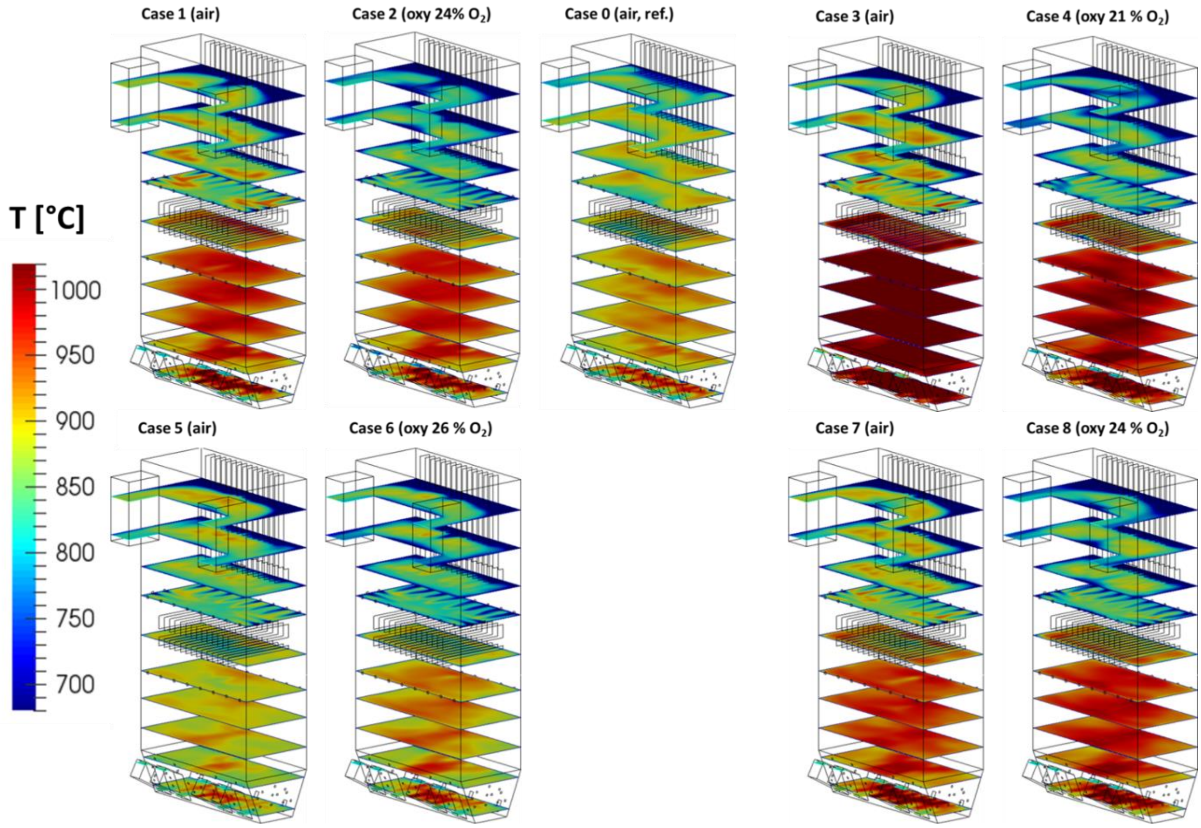


Figure 3. Gas temperature [°C]

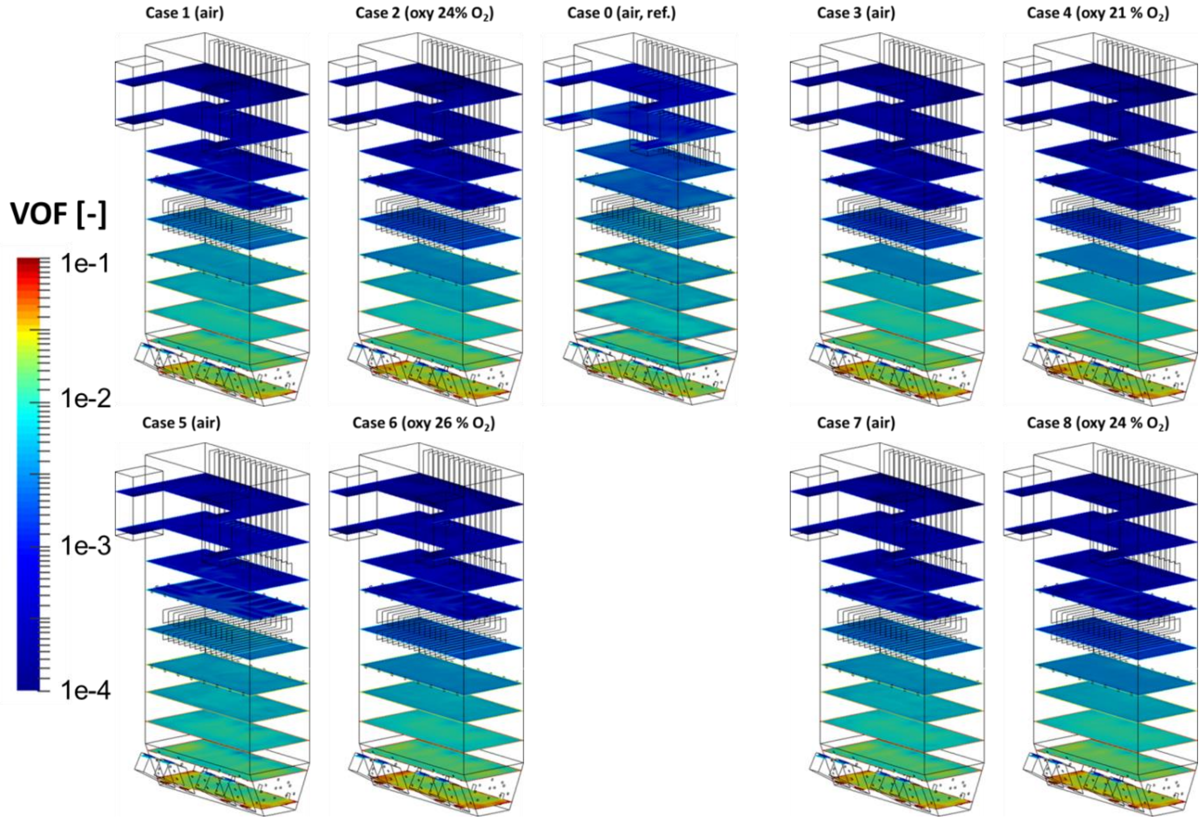


Figure 4. Solids volume fraction (log scale)

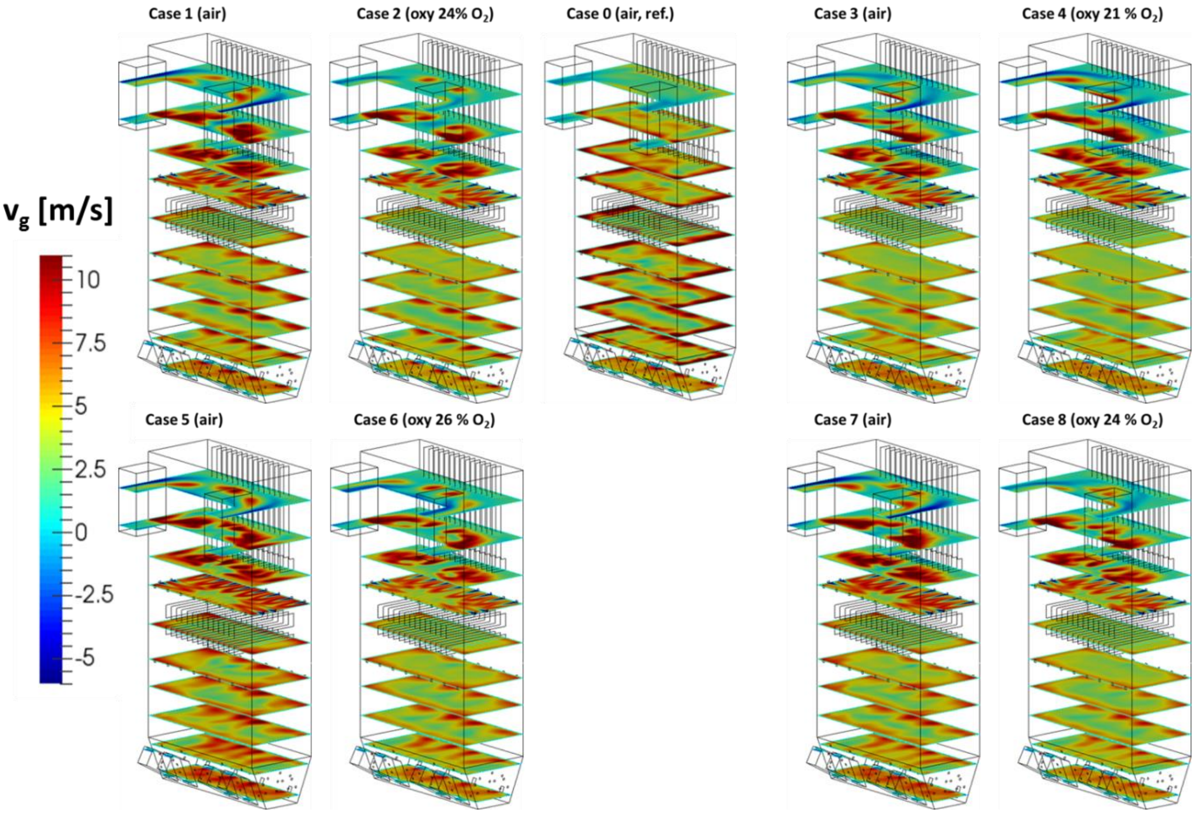


Figure 5. Vertical gas velocity [m/s]

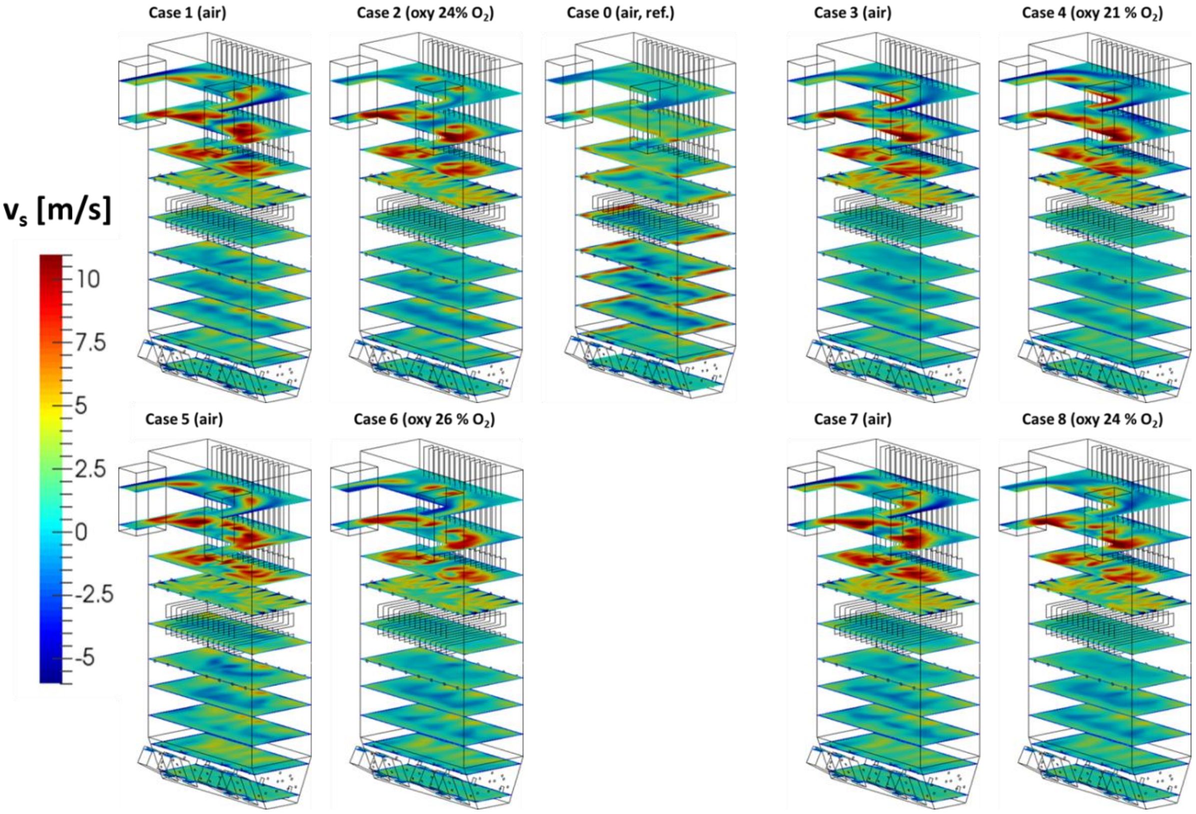


Figure 6. Vertical solids velocity [m/s]

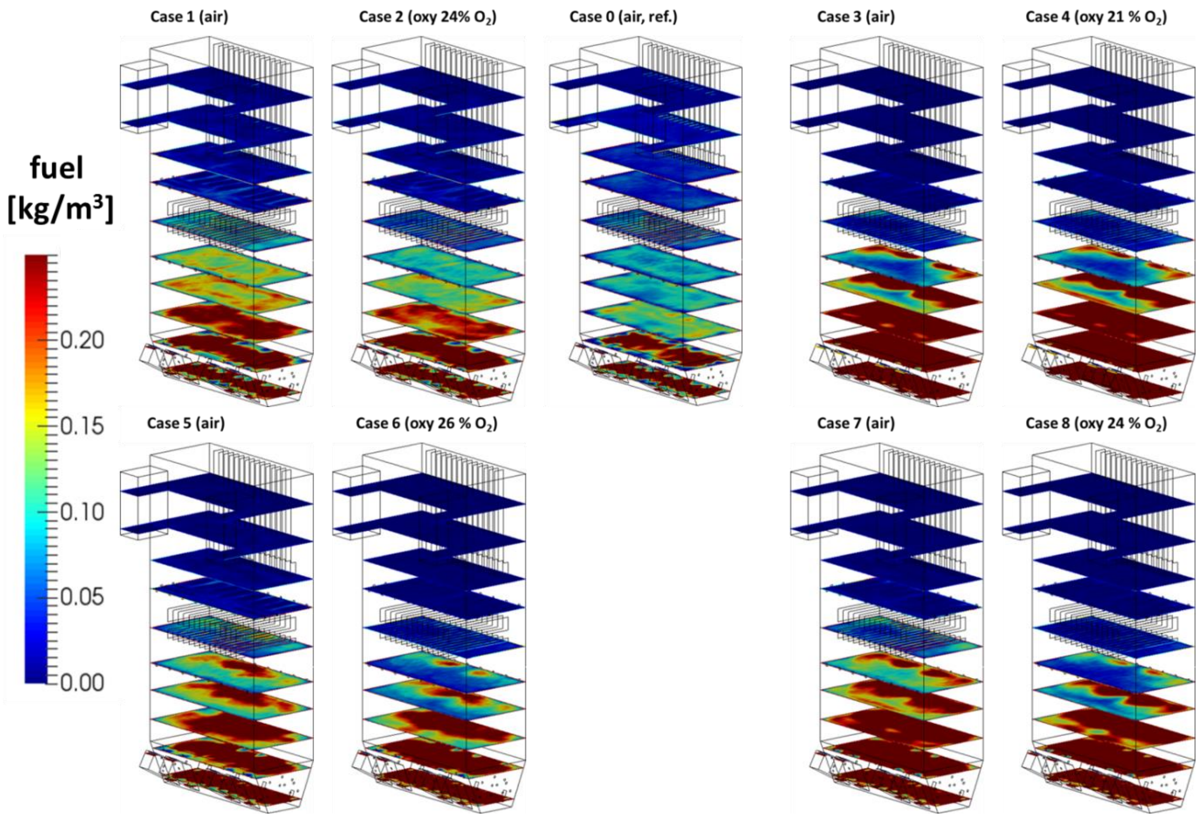


Figure 7. Fuel particle concentration [kg/m^3]

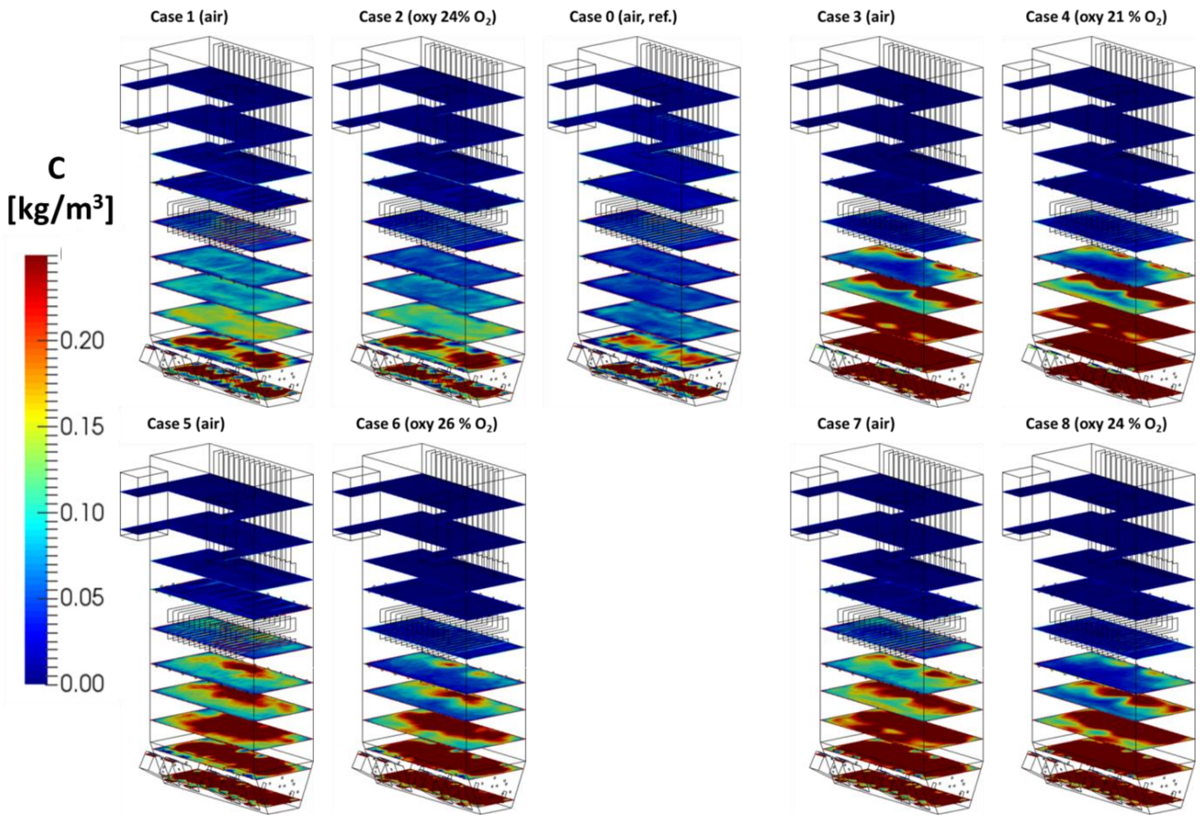


Figure 8. Unburned carbon concentration [kg/m^3]

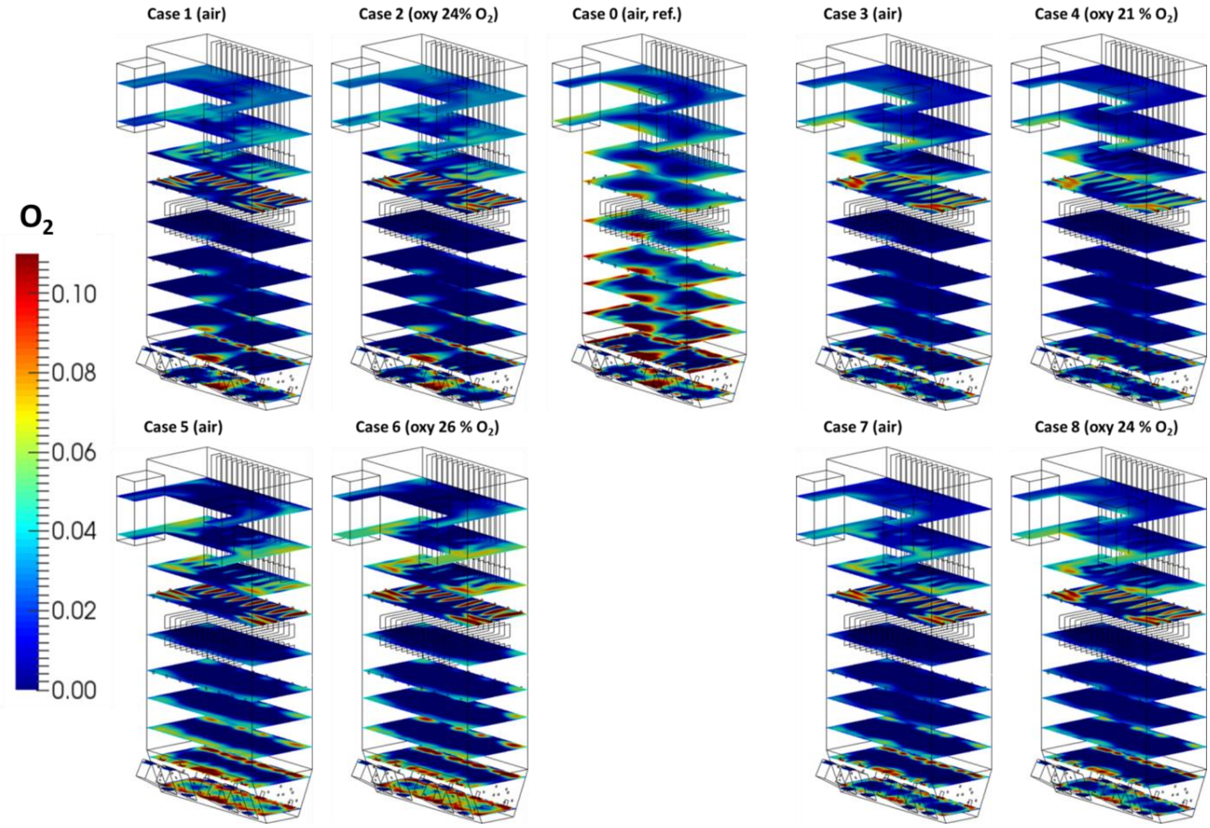


Figure 9. Mass fraction of O_2

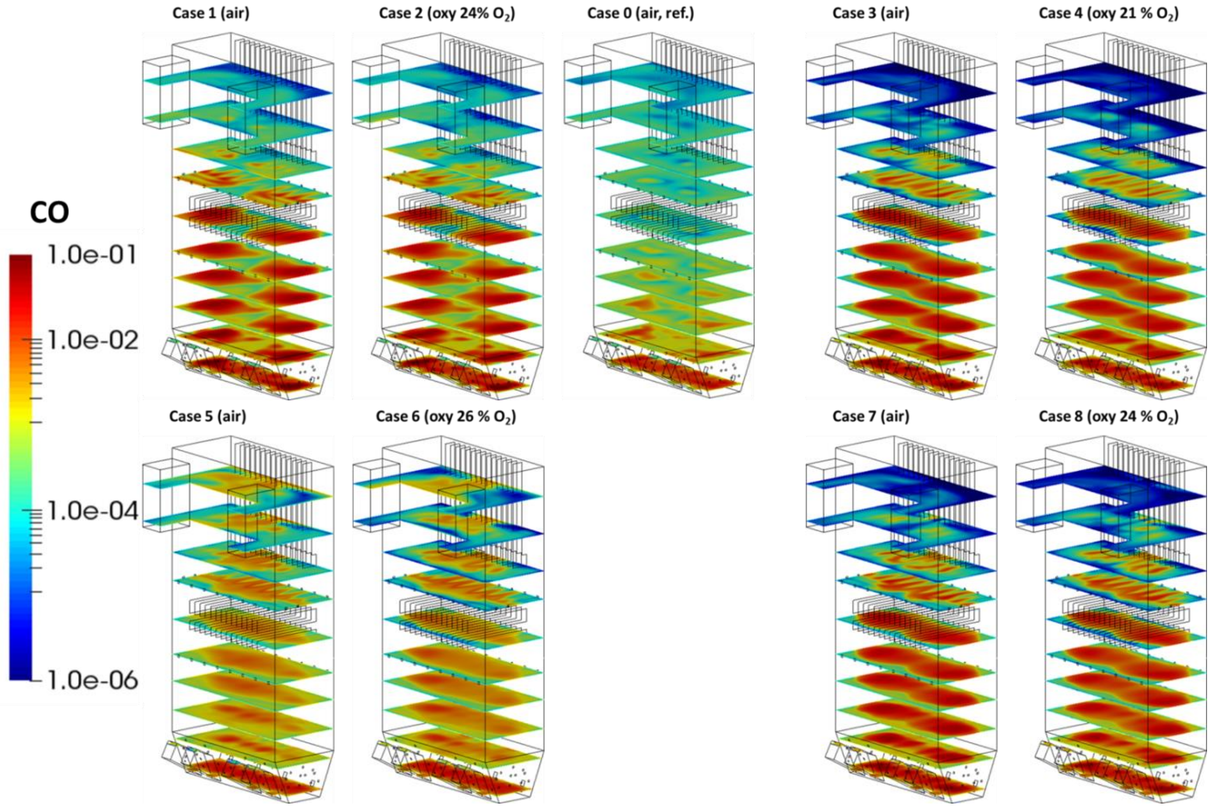


Figure 10. Mass fraction of CO (log scale)

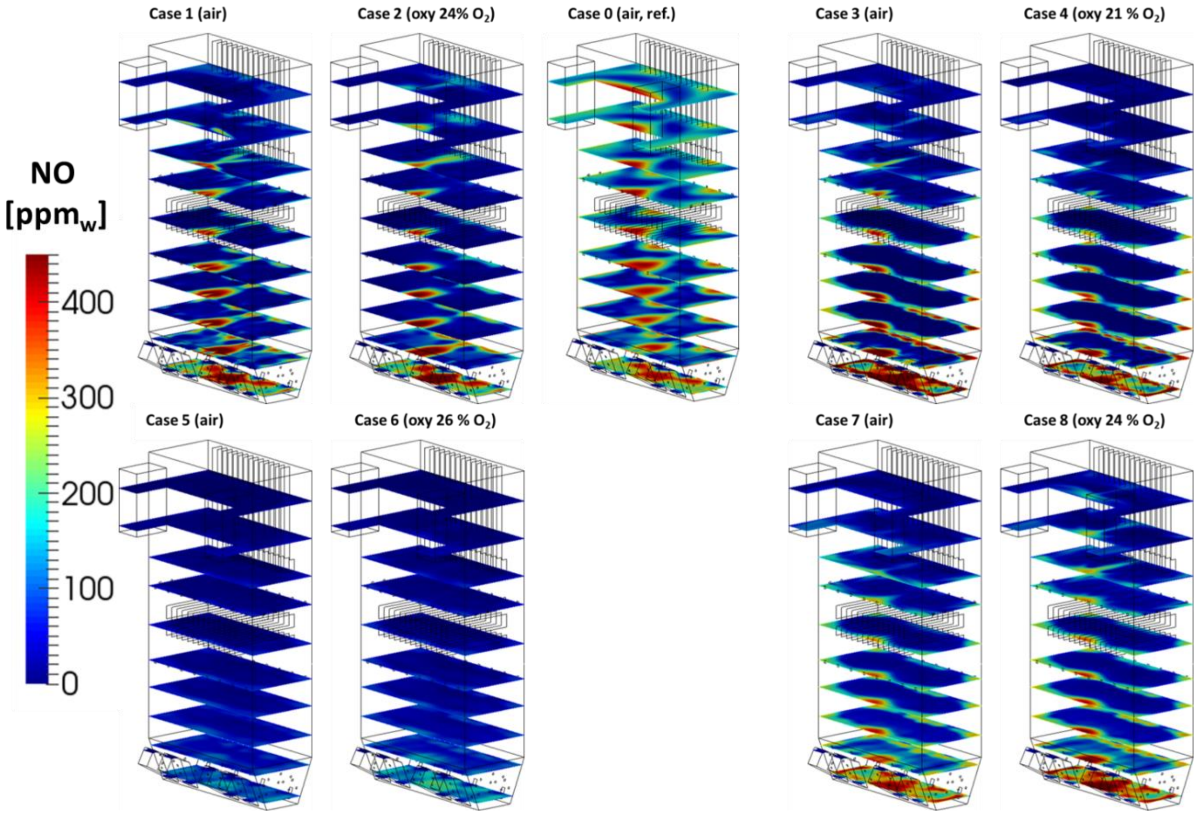


Figure 11. Mass fraction of NO

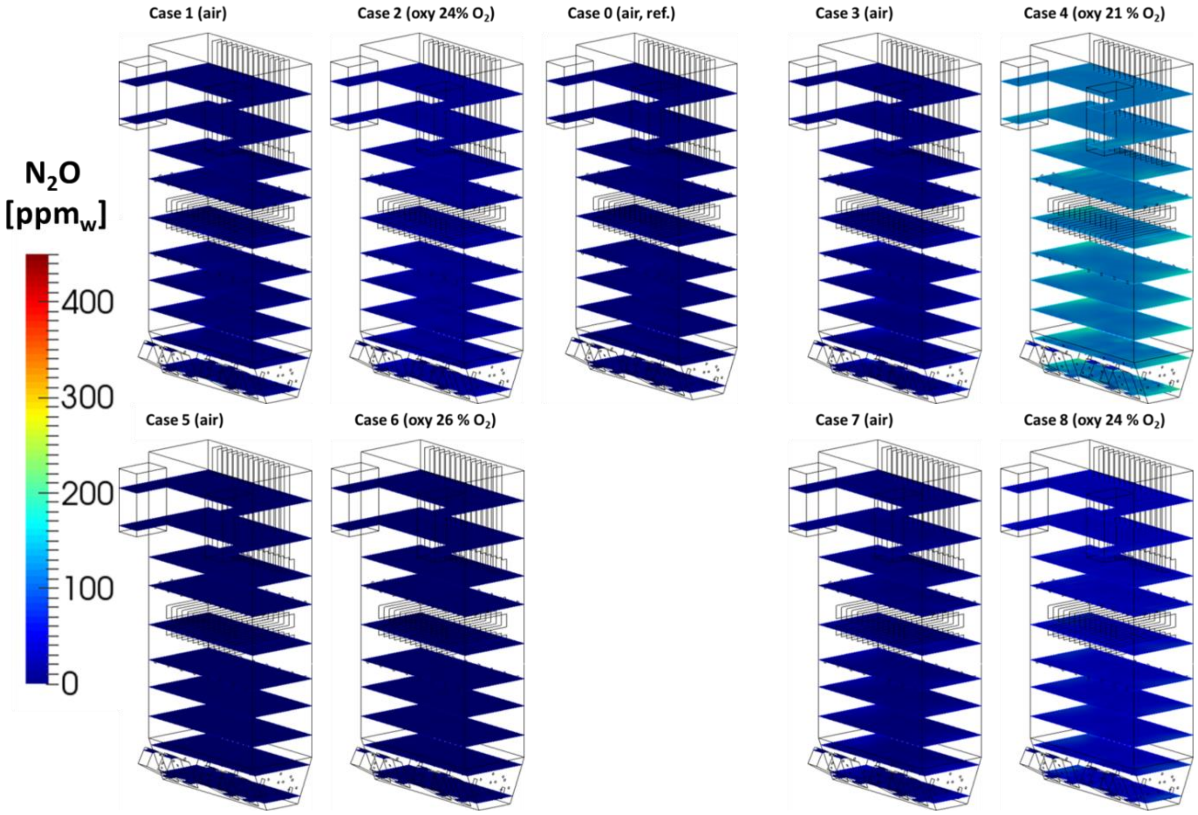


Figure 12. Mass fraction of N_2O

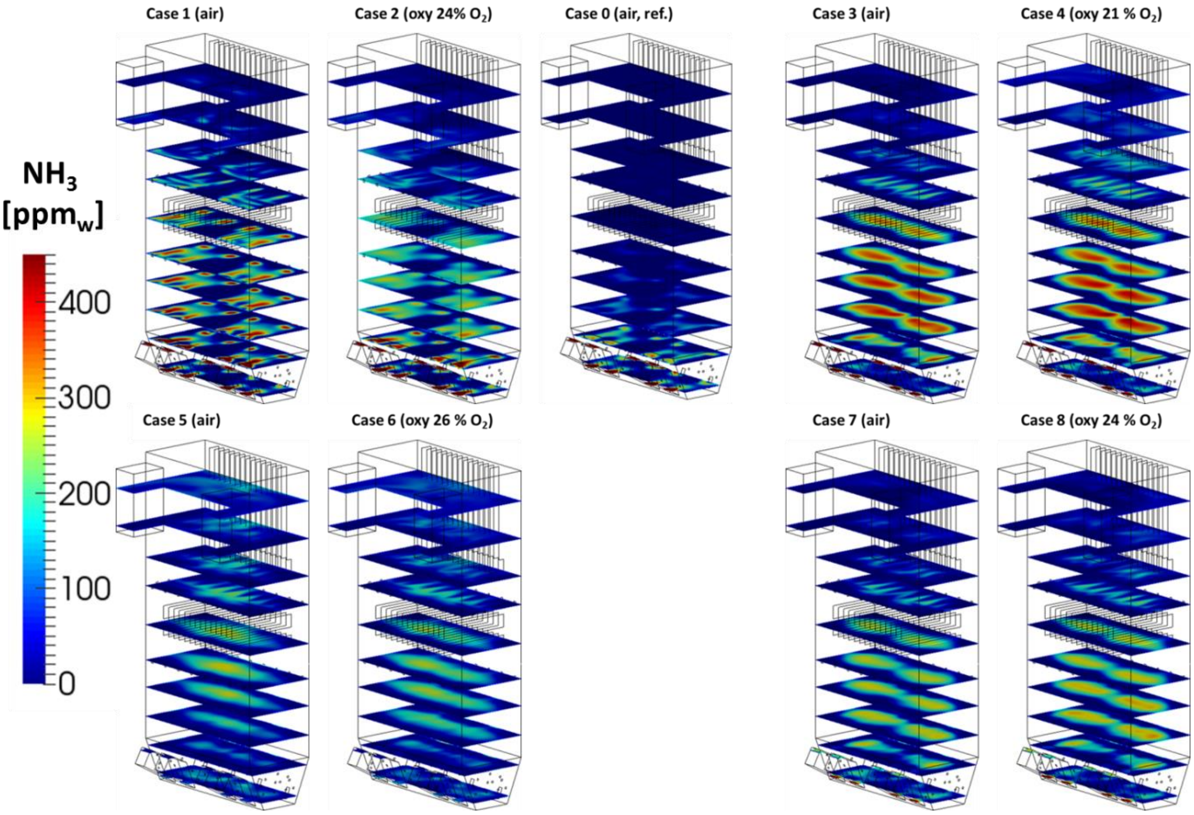


Figure 13. Mass fraction of NH_3

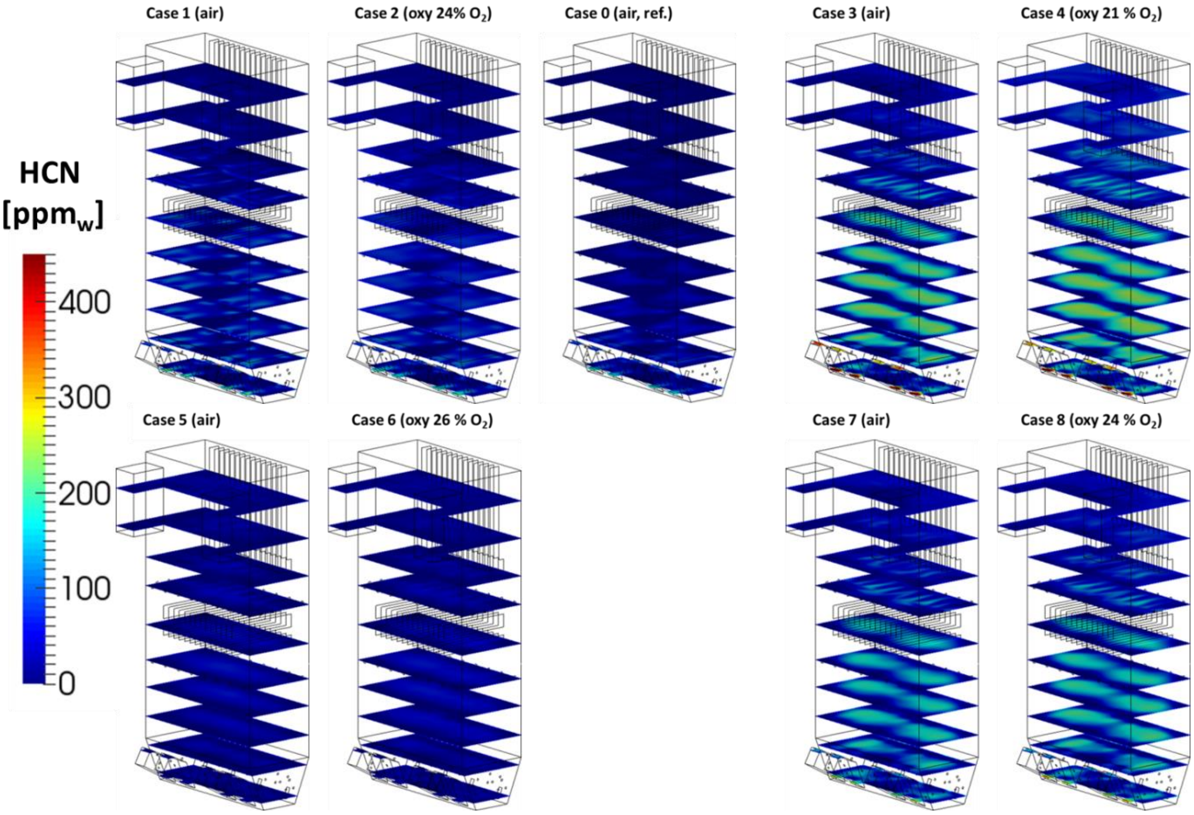


Figure 14. Mass fraction of HCN

5. Conclusions

In the present study VTT's steady-state modelling approach for circulating fluidized beds was applied to simulate air and oxy-fuel firing with different fuels in a large scale CFB furnace. The furnace geometry was chosen to be close to that of the Turow CFB furnace no 3 in Poland. The dimensions were set based on available public boiler data. The Russian Kirkyaskya coal, Finnish forest residue and the 50/50 (energy basis) mixture of those were considered as fuels in addition to Polish lignite, the native fuel of the boiler in question. The over fire air (OFA) concept developed earlier by Fortum and VTT was applied in all cases but one. The normal operating mode without the OFA was simulated for reference. Both air and oxy-fuel combustion cases with the OFA concept were simulated for each fuel considering the full load of the boiler 670 MW_{fuel}. In oxy-fuel cases the feed gas O_2 concentration was varied along with the fuel type such that it was 21 vol-% for coal 24 vol-% for lignite and the fuel mixture and 26 vol-% for pure forest residue. Wet flue gas recirculation was presumed.

In air firing flue gas volumetric flow rates varied remarkably depending on the fuel, but in oxy-fuel firing they were more similar due to the modified feed gas O_2 content.

According to the results the OFA concept efficiently reduces NOx emission in air firing of lignite. At the same time solids circulation decreases and the furnace heat transfer declines moderately. The lower furnace temperature is predicted to increase. In the simulations the unburned carbon flow to the cyclones remained at the original level despite air staging, since the delayed contact with O_2 is compensated by reduced solid circulation and fuel particle entrainment. CO burnout is predicted to be a bit weaker in the OFA case.

In air firing heat transfer and the furnace temperature are simulated to increase and solids circulation to decrease (reduced flue gas flow) along with improving fuel quality (heating value). Fixed carbon and CO burnout depend on freeboard velocity, fuel particle size, fixed C content, fuel char density and gas temperature. The UBC flow and the exit CO concentration are predicted to be higher with forest residue and lignite and lower with coal and the fuel mixture. The simulated NOx and N_2O emission are small with all fuel types thanks to the efficient OFA. The highest emissions are simulated in the coal and the co-firing cases and the lowest with forest residue.

In oxy-fuel firing the furnace performance is more similar with different fuels due to the fuel dependent feed gas O_2 concentration. Compared to air firing the lower furnace temperature and the overall heat transfer decrease with coal (21% O_2), remain similar with lignite and the fuel mixture (24% O_2) and increase with forest residue (26% O_2). The upper furnace temperatures are lower in oxy-fuel cases as a consequence of rise in flue gas heat capacity compared to air combustion (effect of H_2O and CO_2). Solids circulation and the UBC flow are reduced in cases with increased feed gas O_2. The predicted CO emissions are comparable to air firing. Generally the exit NO, HCN, NH_3 and especially N_2O concentrations increase in connection with flue gas recirculation. With coal the decreased furnace temperature also favours N_2O formation over NO.

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