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Oxy-fuel burner investigations for CO2 capture in cement plants

Francisco Carrasco-Maldonado[a]*, Jørn Bakken[b], Mario Ditaranto[b], Nils E. L. Haugen[b], Øyvind Langørgen[b], Simon Grathwohl[a], Jörg Maier[a]

[a]*IFK, University of Stuttgart, Pfaffenwaldring 23, 70569 Stuttgart, Germany*
[b]*SINTEF Energy Research, Trondheim, Norway*

Abstract

Oxy-fuel conditions may have a considerable influence on the cement production process. This paper presents the results of a first validation work aiming to model the combustion behavior under rich CO_2 conditions. The experiments took place in a 500 kWth pulverized fuel combustion rig. A swirl burner is employed to stabilize an air and an oxy-fuel case (29% oxygen in combustion gases). Detailed measurements of temperature and concentrations (O_2, CO_2, CO) along the furnace length are used to validate the simulation work. A commercial CFD software (Ansys Fluent) is employed to simulate both air and oxy-fuel cases. The results from the simulations indicate a good agreement with the measured values. However, some discrepancies are observed in near burner region that may be also be related to the measurement method employed.

Keywords: oxy-fuel, cement, carbon capture

1. Introduction

Oxy-fuel combustion stands as a promising carbon capture technology to significantly reduce CO_2 emissions from industrial combustion processes. Due to a different process layout compared to power industry, as well as different boundary conditions, further investigations and demonstration activities are required to develop the oxy-fuel cement process to maturity. In a full oxy-fuel configuration, both the calciner and the cement kiln are operated under CO_2/O_2 conditions. The full oxy-fuel configuration does not require a complete redesign of the preheating

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* Corresponding author. Tel.: +49-711-685-68935; fax: +49-711-685-63491.
E-mail address: Francisco.carrasco@ifk.uni-stuttgart.de

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tower, which is the case for the partial oxy-fuel process. However, the kiln burner needs to be adapted or redesigned for oxy-fuel operation. The design should consider aspects that are related to oxy-fuel combustion, such as:

- Possible ignition delay under CO_2/O_2 atmospheres
- Altered heat transfer through radiation
- Reduced volume of flue gases
- Influence of the Boudouard reaction ($C + CO_2 \dashrightarrow 2CO$)

Oxy-fuel conditions may have a considerable influence on the clinker burning process. Radiation is the dominant heat transfer mechanism in cement kilns. An important aim of oxy-fuel investigations of cement kilns is to determine to what extend radiation to material is altered and which oxy-fuel configuration (FGR ratio) could produce similar heat transfer profile in the kiln to avoid detrimental effects in clinker quality. In order to validate the CFD model to be used in new kiln burner design with oxy-fuel combustion, CFD simulations of an existing burner with good experimental data are carried out.

2. Experimental Setup

The experiments were done at the 500 kW_{th} pulverized fuel combustion test rig at IFK, University of Stuttgart (see Figure 1).The combustion chamber consists of six cylindrical segments with a total length of 7 m and an inner diameter of 0.8 m. Refractory lining covers the inner surface of the upper four segments of the combustion chamber to a distance of 4 m from the burner.

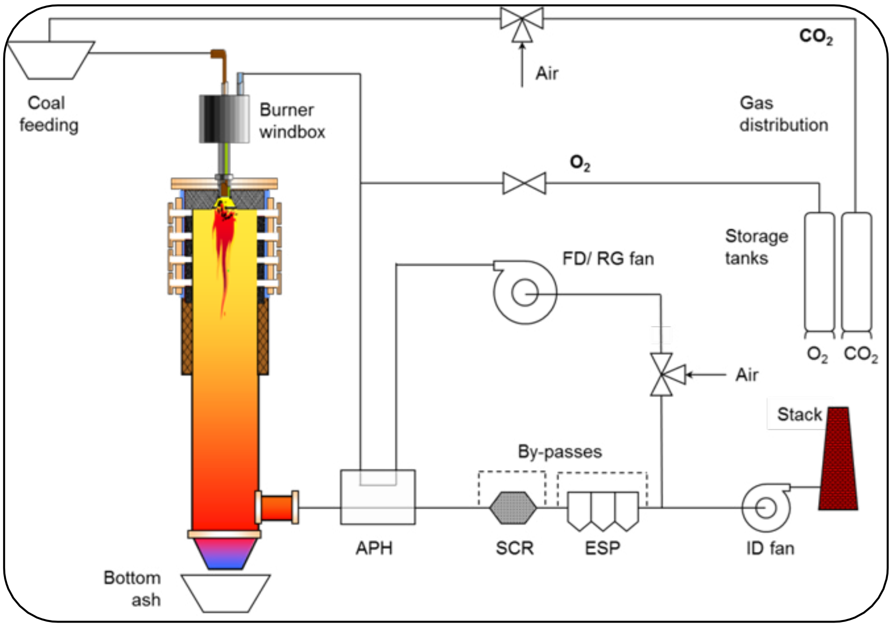

Figure 1 Schematic of the 500 kWth pilot test facility at IFK, University of Stuttgart.

The experimental data were obtained by the combustion of a South African Coal. The raw coal was prepared (pre-dried, crushed and milled) at the University of Stuttgart. The coal particles had a minimum diameter of 1 micron, maximum diameter of 200 micron, mean diameter of 42 micron, and a spread parameter of 1.23. Further data of the coal is given in the table below. The same coal data were used in the numerical simulations.

Table 1. Coal properties and ultimate analysis.

Property	Value
Higher heating value (kJ/kg)	27383
Fixed C (%)	57
Water (%)	1,65
Ash (%)	14.4
Volatiles (%)	27.2
C	67.8
H	4.6
O	9.4
N	1.8
S	0.4

The burner has two inlets. The primary inlet is ring shaped where gas and coal are fed axially, and a secondary ring shaped inlet outside the primary inlet equipped with swirl vanes for the secondary gas.

3. Numerical Setup

The geometry was modelled in 2D and the case was run as 2D axisymmetric swirl. The burner upstream of the inlets to the combustion chamber was not modelled. The different models are listed in the table below. Ansys Fluent 17.0 was used for the CFD simulations. The wall temperature profile was calculated from the IFK experiments, and implemented through a user defined function (UDF). For the oxy-case the temperature profile was set as:

$$\begin{aligned} &\mathrm{X} < 3.5m \rightarrow T = -157.14\mathrm{X} + 1450 \\ &\mathrm{X} > 3.5m \rightarrow T = 900 \end{aligned} \tag{1}$$

For the air case a similar profile was used with slightly different constants corresponding to measured temperatures.

Table 2 Numerical models.

	Ansys Fluent models
Code	Fluent 17.0
	2D-Axisymmetric swirl
Mesh, number of cells	113757 (structured mesh)
Turbulence	k-epsilon, realizable, standard wall functions
	k-omega SST
Chemistry	Species transport, Finite rate/Eddy Dissipation, 2-step reaction.
Radiation	P1 with particle-radiation interaction.
Furnace wall temperature	Profile calculated from IFK experiments. Implemented by an UDF (User Defined Function).
Inlets	Velocity inlet (constant velocity)
Outlet	Pressure outlet

The cylindrical geometry used in the simulations was 5m long and 0.8m in diameter. This is somewhat shorter than the actual combustion chamber, but covers the area of most interest. Both air and oxy-fuel cases were simulated. For turbulence, the k-omega SST model was found to give the best results, and was used in the final simulations (as shown in the figures below). Mass flows for the air and oxy-fuel cases used in the numerical simulations (and experiments) were as in Table 3. Both inlets were set as velocity inlets in Fluent. For the secondary inlet (swirl) components of axial and tangential velocity were given. The coal was fed through the primary gas inlet at the same velocity as the gas.

The combustion was modeled with Finite rate/Eddy-Dissipation. The eddy-dissipation model assumes that reactions are fast and that the system is purely mixing limited. When that is not the case, it can be combined with finite-rate chemistry. In that case, the kinetic rate is calculated in addition to the reaction rate predicted by the eddy-dissipation model.

The slowest reaction rate is then used:

– If turbulence is low, mixing is slow and this will limit the reaction rate.
– If turbulence is high, but the kinetic rate is low, this will limit the reaction rate.

Table 3: Inlet boundary conditions.

		Air	Oxy29
Fuel mass flow	kg/h	41.5	41.5
Primary gas mass flow (Air/CO_2)	kg/h	43	67
Primary gas temperature	K	308	308
Secondary gas mass flow	kg/h	362	303
Secondary gas temperature	K	468	471
Composition secondary gas:			
O_2	Vol%	21	36.0
N_2	Vol%	79	5,8
CO_2	Vol%	0	47.3
H_2O	Vol%	0	10.9

4. Comparison of experimental and numerical results

A comparison of experimental and numerical data for the oxy-fuel case is shown in the figures below. Overall, the numerical data agrees well with the experimental data for both temperature and major species. Figures 2 and 3 show the temperature distribution in air and oxy-fuel conditions respectively. In these figures, there is an equivalent level of agreement with the simulations, which is poorest at the boiler centerline. High levels of turbulence along the centerline is usual in swirling flows and can be difficult to measure experimentally with intrusive gas sampling method. The results indicate that shifting from air to oxy-fuel atmosphere was well managed by the CFD with a relatively standard set up. Due to the resolution of the measurement method, the near burner region with strong gradients and swirling motion is not captured in enough detail for a comparison, but the agreement in absolute values of concentration and temperature is a good indication that the main features of combustion in the boiler are represented. A discrepancy close to the wall should be noted. The reason for this is so far unknown. Figure 6 shows that measured and calculated values of CO is of the same order of magnitude. Further down from the burner (x > 1.0m), there are no significant changes of CO concentration. However, the simulation gives lower concentration than measured. This is probably due to the fast chemistry applied (Finite rate/Eddy-Dissipation). In addition, only volumetric reactions were considered. This means that slower particle surface reactions were not accounted for. It is therefore reasonable that equilibrium is reached faster in the simulations.

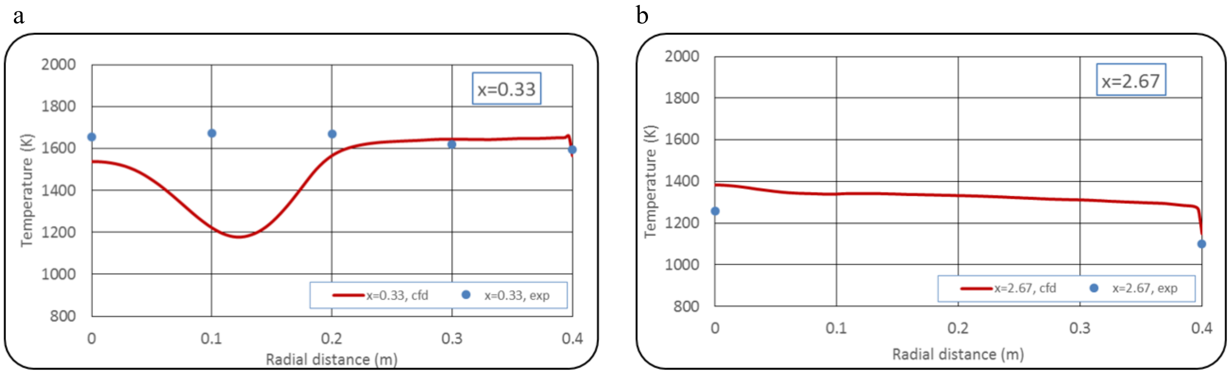

Figure 2 Comparison of experimental and simulated data for temperature at (a) 0.33 and (b) 2.67 meters from the burner for the air case.

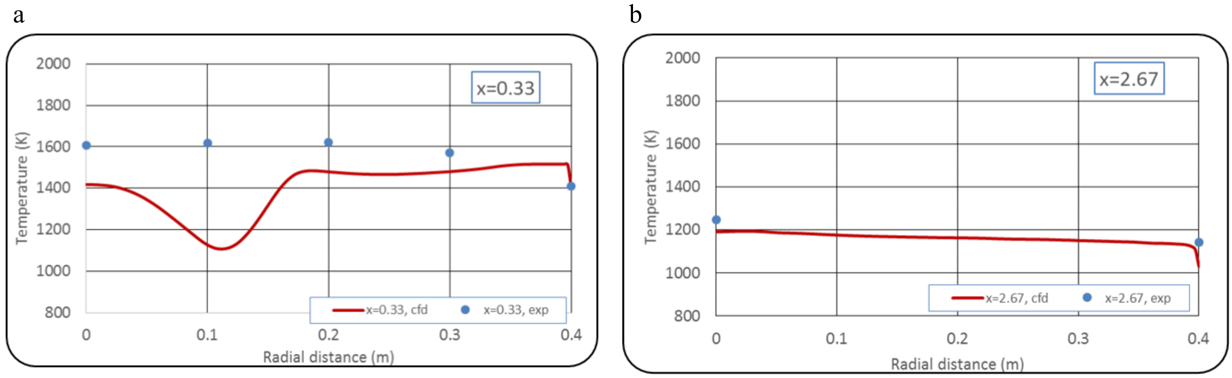

Figure 3 Comparison of experimental and simulated data for temperature at (a) 0.33 and (b) 2.67 meters from the burner for the oxy-fuel case.

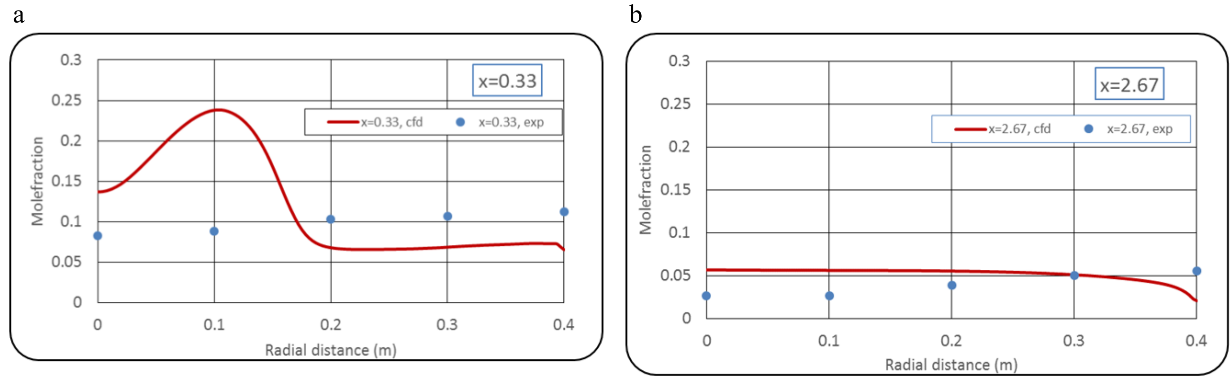

Figure 4 Comparison of experimental and simulated data for O_2 at (a) 0.33 and (b) 2.67 meters from the burner for the oxy-fuel case.

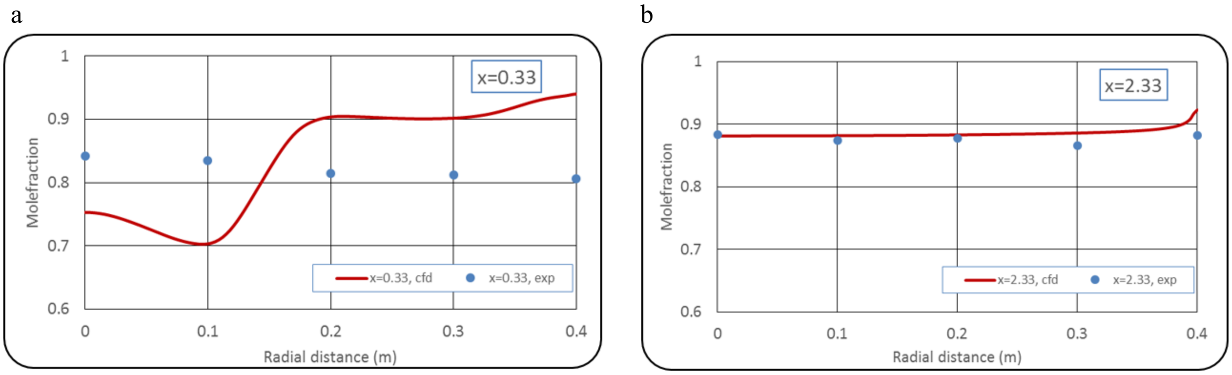

Figure 5 Comparison of experimental and simulated data for CO_2 at (a) 0.33 and (b) 2.33 meters from the burner for the oxy-fuel case

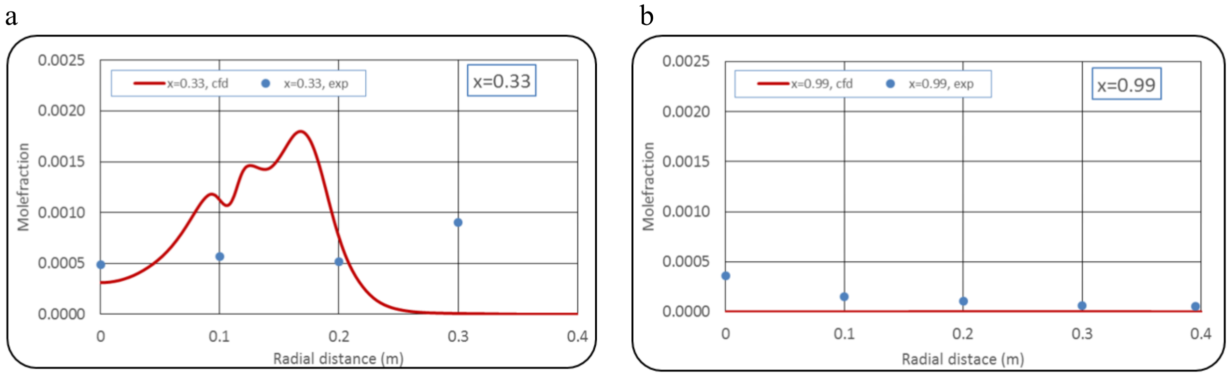

Figure 6 Comparison of experimental and simulated data for CO at (a) 0.33 and (b) 0.99 meters from the burner for the oxy-fuel case.

5. Conclusions and further work

The validation of the numerical model against the experiments have been successful. Good results have been obtained for both the air case and the oxy-fuel case. In both cases, the volatiles burn out very quickly. Two different turbulence models were tested, i.e. k-epsilon and k-omega. For a swirling flow, the k-omega model was most in accordance with the experimental results, and will be used for further numerical simulations. The burner that will be used in the next test campaign is a downscaled kiln burner design with 8 primary air nozzles. Four cases will be investigated, one air and three oxy-mode cases. The four cases will be investigated both numerically and experimentally. Due to the fact that there are 8 individual high speed nozzles in the new burner, the numerical model must be in 3D. The high velocities also bring on further challenges compared to the existing burner. Main goals of the investigation include determining the suitability of the prototype burner for oxy-fuel operation and the investigation of which oxy-mode that produces heat flux profiles similar to conventional air combustion. Besides heat flux measurements, gaseous emissions, burn-out, as well as the effects of dust concentration to evaluate particle radiation effects, will also be investigated.

6. Acknowledgements

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