Development of CFB Technology to Provide Flexible Air/Oxy Operation for a Power Plant with CCS

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DEVELOPMENT OF CFB TECHNOLOGY TO PROVIDE FLEXIBLE AIR/OXY OPERATION FOR A POWER PLANT WITH CCS

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ABSTRACT

Fuel flexibility is one of the most important benefits of circulating fluidized bed (CFB) combustion, but it sets challenges for boiler design to reach high efficiency, low emissions and excellent controllability with different kinds of fuels and their blends. Oxygen-firing in CFB conditions requires additionally a substantial number of process and design variations. Foster Wheeler is developing its CFB boiler technology toward a Flexi-Burn^{TM} CFB application, which features the additional capability to operate in normal air mode as well as oxy-fuel mode with carbon capture and storage (CCS).

VTT Technical Research Centre of Finland has unique small scale (30-100 kW) circulating fluidized bed combustor (CFBC) applicable for both oxygen and air combustion research. The combustor is equipped with O_2 and CO_2 feed from gas tanks and also with flue gas recirculation for demonstrating real oxygen-firing conditions. In the pilot scale CFBC combustion process and its sub-processes can be studied very effectively at well controlled and measurable conditions. The process knowledge and development of models combined with high quality data are the key elements when improving the design of the CFB boiler.

VTT and Foster Wheeler have a long history of co-operation in research and development of CFB combustion technology, and development of oxygen-firing CFB since 2004. Several projects containing experimental test campaigns combined with development of models and design tools has been carried out. The latest co-operation project in November 2008 was an extensive CFB-pilot test campaign with Polish bituminous coal, which will be also used in the 460 MW_e supercritical CFB power plant at Łagisza. Combustion profiles and performance, emission levels and sulfur capture by limestone were measured at different process conditions for air and oxygen combustion modes. A one dimensional design model owned by Foster Wheeler has been validated for the VTT's pilot scale CFBC, and is used as basis for further development of the model. The developed model based on small scale experimental results can be utilized after validation in designing of commercial scale CFB boilers.

In this paper the results of the CFB-pilot test campaign with Polish bituminous coal (Łagisza's coal) at air and oxygen combustion conditions are presented. In addition to high concentrations of CO_2 and H_2O in gas, also differences in emissions formation and capture were obtained. Test balances were calculated with the current version of the one dimensional design model. Modeled gas profiles (O_2, CO_2 and CO), temperature profiles, and unburned carbon in fly and bottom ashes were compared to measured values. Experiments done at test facilities of different scales provide information about the differences between air and oxygen combustion, and the acquired knowledge is being incorporated in boiler design tools. Preliminary development and design of an integrated Flexi-Burn CFB power plant has already been conducted in both air and oxy-fuel mode, and the continuing work aims at more extensive and detailed knowledge and designs.

INTRODUCTION

The fuel flexibility is one of the most important benefits of CFB combustion but on the other hand wide fuel selection sets high demands for boiler design to meet high efficiency, low emissions and excellent controllability with different kind of fuels and their mixtures. Oxygen-firing in CFB conditions offers great number of process and design variations, for example O_2 contents of the oxidant flows can be varied widely and external solid heat exchangers can be used to extract heat from the circulating solids or bed material to maintain desired combustor temperature. These two special design features of CFB boiler – fuel flexibility combined with air- and oxygen-firing (with CCS) possibility – are incorporated in the Flexi-Burn CFB technology developed by Foster Wheeler. VTT Technical Research Centre of Finland is co-operating with Foster Wheeler in developing CFB technology by experimental work and development of modeling and design tools.

VTT has a small scale (30-100 kW) circulating fluidized bed combustor (CFBC) applicable for oxygen and air combustion research. In a pilot scale CFB reactor combustion process and its sub-processes can be studied very effectively at well controlled and measurable conditions. The process knowledge with design tools validation and development of models combined with high quality data are the key elements in designing Flexi-Burn CFB boiler. A test campaign was carried out in both air and oxygen-firing conditions with Polish bituminous coal in order to produce necessary data to deepen the understanding of Flexi-Burn combustion technology and to extend modeling capabilities under those conditions.

CFB COMBUSTOR PILOT PLANT

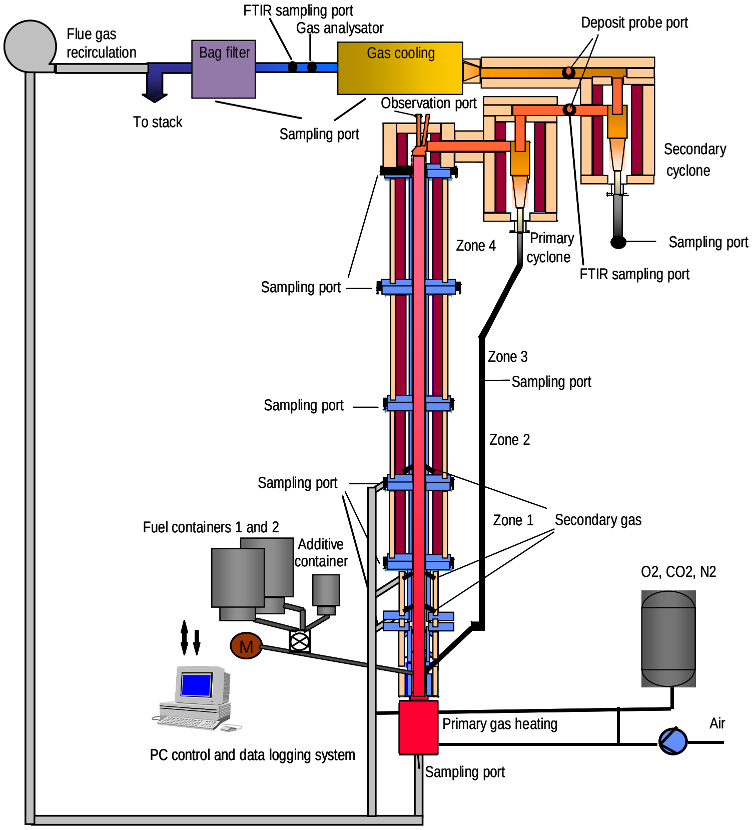

Figure 1. CFB combustor pilot.

CFB combustor pilot plant is illustrated in Figure 1. The height of the riser is 8.0 m and the inner diameter is 167 mm. The reactor is equipped with several separately controlled electrically heated and water/air cooled zones in order to control the process conditions (for example O_2 level, temperature and load) almost independently. Bed temperature can be controlled by different water cooled tube-spiral type heat exchangers (installed before the tests) and by three controllable water cooled tubes in the bed area. The combustor is controlled by a computer to which all measurement data is collected.

Bed material (bottom ash) can be sampled and discharged continuously or periodically above the grid by bottom ash screw and circulation material sample can be taken below the primary cyclone (from the solids circulation loop). There are four ports along reactor freeboard area for gas and solid material sampling. Fly ash samples can be taken from the secondary cyclone, gas cooler, and baghouse. The combustor is equipped with FTIR spectrometer and traditional on-line analyzers of main flue gas compounds. Typically FTIR-analyzer measures gas composition after the primary cyclone and traditional analyzers after the gas cooler.

Fuels can be fed into the combustor through two separated fuel containers. Fuel containers are mounted on the scales in order to determine mass flows of fuels. Limestone, sand and other additives can be fed into combustor to the same level as fuels, or into the circulating material loop below the primary cyclone.

Flue gas recirculation system was built up to demonstrate real oxygen combustion. Oxygen combustion tests can be carried out also with bottled O_2 and CO_2 gases. Recirculation system contains recirculation fan with flow measurement and control equipment. After the recirculation fan flue gas is divided into primary and secondary gas lines. The flow rate is measured in the primary gas line, and the both lines have own flow controlling valves. The oxidant gas can consist of air, N_2, O_2, CO_2, recirculated flue gas, or mixtures of these. Gas is divided into primary gas fed through the grid and secondary gases fed to up to three different levels of the combustor. The gas compositions can be adjusted independently for primary and secondary gases.

EXPERIMENTAL

The test program (Table 1) for the CFB-pilot experiments consisted of seven air- and seven oxygen-firing tests balances. The varied parameters in the tests were load, temperature level, limestone calcium to fuel sulfur ratio (Ca/S) and air staging. One of the air-firing tests was carried out with 7% flue gas recycling and one oxygen-firing test with bottled O_2/CO_2 feed (no flue gas recycling).

Table 1. Test matrix.

	Test number	**Fuel power** kW	**T_{bed}** °C	**$T_{freeboard}$** °C	**Ca/S, total** molar ratio	**FG RC*** %, wet	**Feed gas O_2** %, wet	**Notes**
Air	1	31.8	815	797	1.5	0	20.8	Low load
	2	51.4	866	865	2.1	0	20.8	Full load (base test)
	3	52.6	868	870	2.1	0	20.8	Fouling at temp.T2
	3b	51.4	854	866	2.1	0	20.8	Air staging
	4	52.2	874	877	1.3	0	20.8	Low Ca/S
	5	48.0	893	895	2.2	0	20.8	High temp.
	6	51.4	893	895	1.3	0	20.8	High temp., low Ca/S
	7	32.5	799	805	1.7	7	19.7	FG RC, low load
Oxygen	8	69.4	784	811	1.9	70	24.1	Low temp.
	9	74.8	858	870	2.1	63	29.2	Medium temp.
	10	89.6	913	926	2.0	64	28.8	High temp.
	11	89.7	909	921	1.2	64	28.0	High temp., low Ca/S
	12	75.0	864	874	1.2	65	27.7	Medium temp., low Ca/S
	13	73.9	867	876	2.6	64	28.4	Medium temp., high Ca/S
	13b	73.3	866	875	2.1	64	28.3	Medium temp. (repetition)
	14	72.7	868	873	2.1	0	27.3	Bottled CO2 feed

The fuel used in the tests was Polish bituminous coal (used also in 460 MW_e CFB power plant at Łagisza). A commercial limestone called GS500SB was used for sulfur capture inside the combustor.

Table 2. Analyses of Polish bituminous coal and GS500SB limestone.

Coal analysis

Total moisture	weight-%	14.2
Ash content (815 °C)	w-%, dry	23.6
Volatile matter	w-%, dry	30.3
Fixed carbon (calculated)	w-%, dry	46.1
C	w-%, dry	58.9
H	w-%, dry	3.80
N	w-%, dry	0.87
S	w-%, dry	1.60
O (calculated)	w-%, dry	10.8
Ca	w-%, dry	0.48
Gross calorific heat value	MJ/kg, dry	23.83
Net calorific heat value	MJ/kg, dry	23.01
Net calorific heat value as received	MJ/kg	19.40

Limestone analysis

Ca	w-%, dry	36.3
Mg	w-%, dry	0.66
S	w-%, dry	0.03
$C_{carbonate}$	w-%, dry	11.38

Comprehensive analysis of the prepared coal was made from one representative sample, including proximate and ultimate analyses (Table 2**Error! Reference source not found.**). Fuel samples during each test were collected and moisture, ash content (815ºC) and sulfur were analyzed from these samples for balance calculations. One comprehensive analysis including calcium, magnesium, sulfur and moisture was made from prepared limestone sample (Table 2**Error! Reference source not found.**).

During each test run the ashes were sampled at regular intervals. The ash samples included: 1) bottom ash, 2) circulation material from the downcomer of the 1st cyclone, 3) ash from the downcomer of the 2nd cyclone, 4) ash from the gas cooler, and 5) ash from the baghouse. All the ashes sampled and discharged during each test run were collected and weighed to define the ash balance and split. Also the solids circulation flow rate through the 1st cyclone was measured. Three separate fly ash samples (3-5) were mixed in the ratio of mass extracted from the combustor at different sampling points to produce one representative fly ash sample per each test. From bottom ash, solids circulation material and fly ash sample of each test were analysed: 1) total carbon, 2) carbonate carbon, 3) combustible carbon, 4) total sulfur, and 5) HCl soluble calcium.

The gas and solid profiles along the furnace height were measured during the specified test runs (air-firing tests 1, 2 and 3b, and oxygen-firing tests 8, 9, 10 and 14). Temperature and pressure profiles along the riser were measured during all the tests. The continuously operated analyses of gaseous emissions included O_2, CO, CO_2, NO_x (NO+NO_2), and SO_2. Gas measurements were complemented with FTIR gas analyzer (H_2O, CO_2, CO, NO, NO_2, N_2O, SO_2, HCl, CH_4). Location of FTIR-measurement point was at the flue gas line between primary and secondary cyclones.

TEST RESULTS

Generally, the main gaseous emissions (expressed as mg/MJ) were on the same level or lower in oxygen-firing compared to air-firing as seen in Figure 2. Concentrations (as ppm or %) of emissions were typically higher in oxygen-firing due to the fact that flue gas flow to stack is about fifth of flue gas flow of corresponding air-firing test. The oxygen-firing test 14 was carried out by simulating flue gas recirculation with bottled CO_2. The main emissions were on the same level in test 14 compared to air-firing test with similar conditions (tests 2-3) which leads to a conclusion that flue gas recirculation has a major effect on low emissions in oxygen-firing. It should be noted that the emission values measured in a small scale test rig cannot be applied directly for large scale boilers. For instance residence time effects may be significant, requiring model based analysis of the test results for making performance predictions for larger scale.

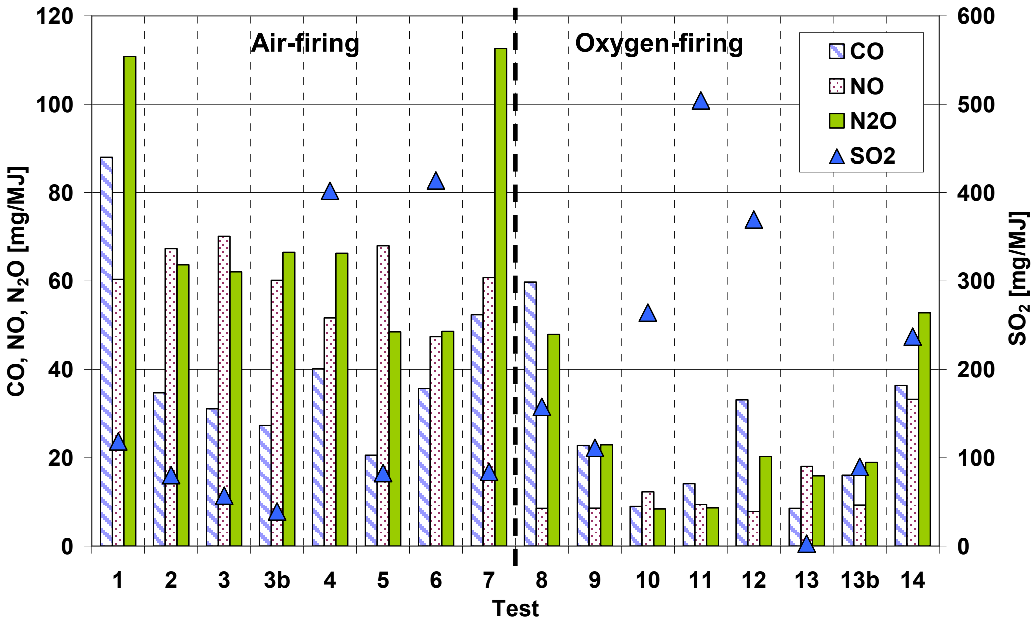

Figure 2. Main emissions (expressed as mg/MJ) of air- and oxygen-firing tests.

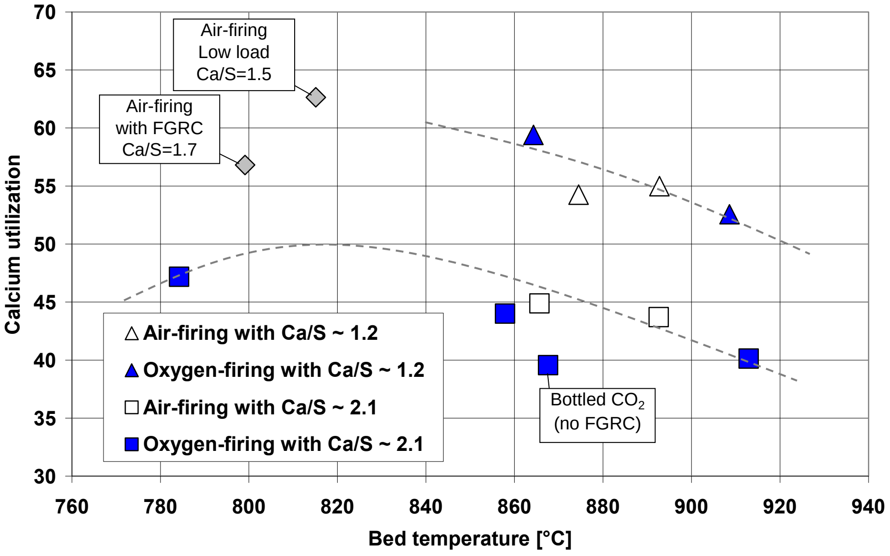

Figure 3. Calcium utilization rates of air- and oxygen firing tests.

Calcium utilization rate was calculated for air- and oxygen firing tests. Calcium utilization rate [%] describes the share of calcium utilized for sulfur capture, and it is defined as sulfur retention [%] per total calcium to fuel sulfur molar ratio [mol/mol]. Figure 3**Error! Reference source not found.** illustrates the calcium utilizations for air- and oxygen-firing tests. Sulfur capture efficiencies were very similar for both combustion modes at temperature level 860-910°C. With lower Ca/S-ratio (about 1.2) calcium utilization was higher than with Ca/S ratio 2.1, as expected. Test 14 was carried out with bottled O_2/CO_2 feed. Calcium utilization was some 5%-points lower with bottled gases, implicating that flue gas recycle improves sulfur capture by prolonging the reaction time between SO_2 and limestone.

Flue gas recirculation (about 7% from total flue gas) was tested in air-firing on partial load (test 7). Clear effect on sulfur capture efficiency can not be seen with that moderate flue gas recirculation: compared to low load test without FGRC (test 1) SO_2 emission was a bit lower but also calcium utilization was lower due higher Ca/S-ratio. At partial load sulfur capture efficiency was better that at higher loads, mainly due to better temperature level for sulfur capture and probably due longer residence time of limestone particles inside the combustor.

From the sulfur emissions point of view the main difference between air- and oxygen-firing is related to reactions of limestone and sulfur capture under high CO_2 concentrations. Depending on the temperature and gas CO_2 concentration limestone will calcinate to calcium oxide (CaO) or remain as calcium carbonate ($CaCO_3$). Under air-firing conditions $CaCO_3$ calcinates to CaO and reacts then with SO_2 forming calcium sulfate ($CaSO_4$). If calcination is hindered due to high partial pressure of CO_2 the sulfur capture can take place through the reaction which is called direct sulfation reaction between $CaCO_3$ and SO_2. Typically with high temperatures (above 900ºC) conditions are favorable for CaO and with low temperatures (below 800º) conditions are favorable for $CaCO_3$. In some cases, conditions inside furnace can alternate along the furnace height and solids circulation loop being on both sides of the equilibrium. The equilibrium curve of $CaCO_3$ and CaO (according to Stantan) was calculated along the furnace height for the oxygen-firing tests 8, 9, 10 and 14 in which gas profiles were also measured (Figure 4).

From Figure 4 it can be seen that conditions were very favorable for $CaCO_3$ in test 8, and very favorable for CaO in test 10. Conditions in the test 9 are more favorable for CaO than for $CaCO_3$, and conditions of test 14 were in transition zone between $CaCO_3$ and CaO. From the collected ash samples forms of calcium compounds – $CaCO_3$, CaO and $CaSO_4$ – were determined. Share of calcium compounds in bottom ashes for tests 2, 8, 9, 10 and 14 are presented in Figure 5. Air-firing test 2 is included for comparison with oxygen-firing test 9 with similar temperature levels. These analyses support the expected calcium behavior in different CO_2 partial pressures and temperatures. Bottom ash of test 8 contains no CaO, and ash of test 10 contains almost no $CaCO_3$. Bottom ash of test 9 contains also some $CaCO_3$ and ash of test 14 contains more $CaCO_3$ than CaO. It must be noted that there is some inaccuracy in the measurements and/or the applied equilibrium curve of $CaCO_3$/CaO. In the literature there is some variation in the equilibrium curves especially in the temperature range of test 9. The calcium utilization was high in test 8 with low temperature and $CaCO_3$ conditions (see Figure 3**Error! Reference source not found.**). In oxygen-firing test 10 with clearly CaO favorable conditions, calcium utilization was low as it was also with similar air-firing conditions (test 5).

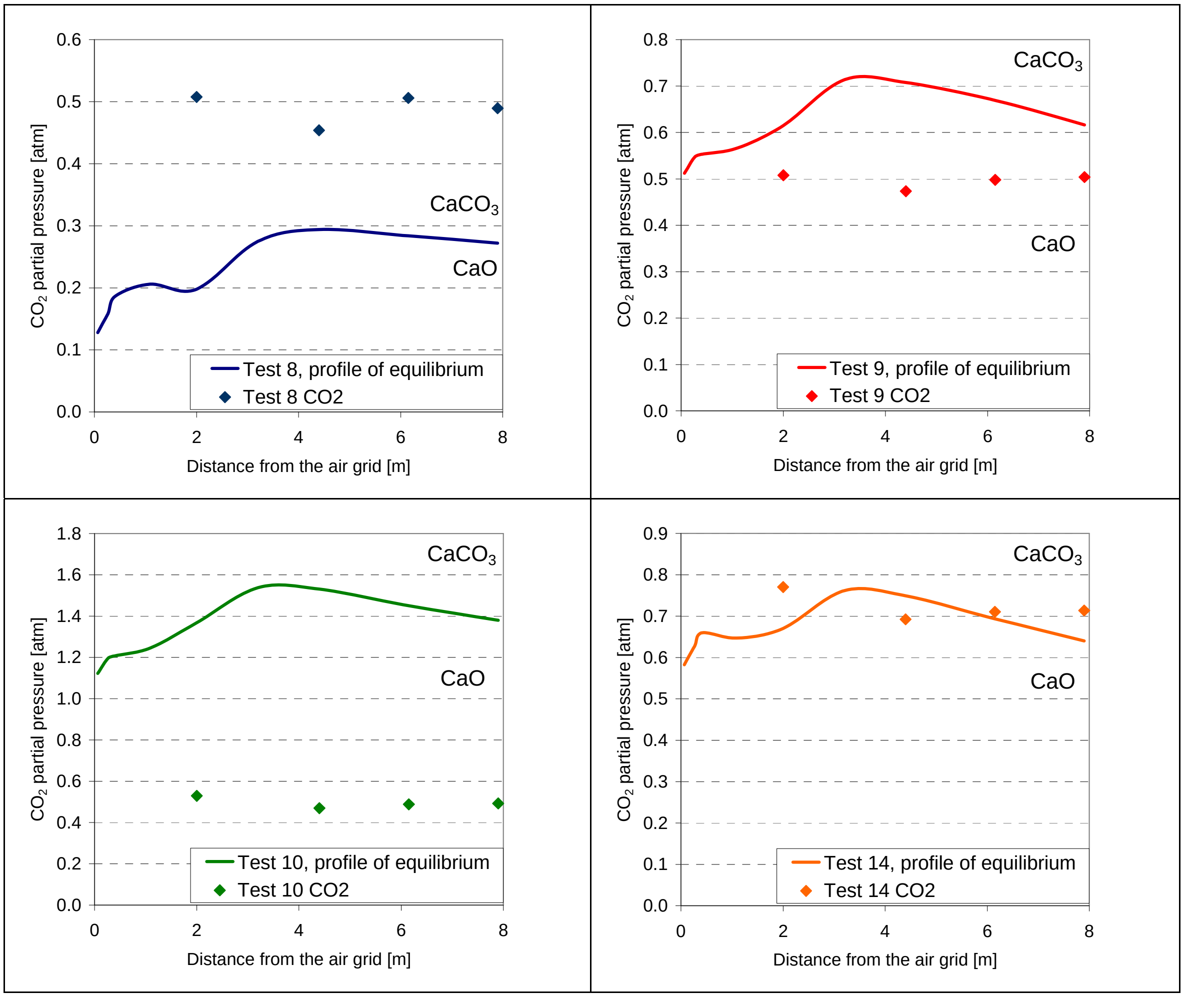

Figure 4. Profile of equilibrium for $CaCO_3$/CaO (according to Stantan) and measured partial pressures of CO_2 along the furnace height.

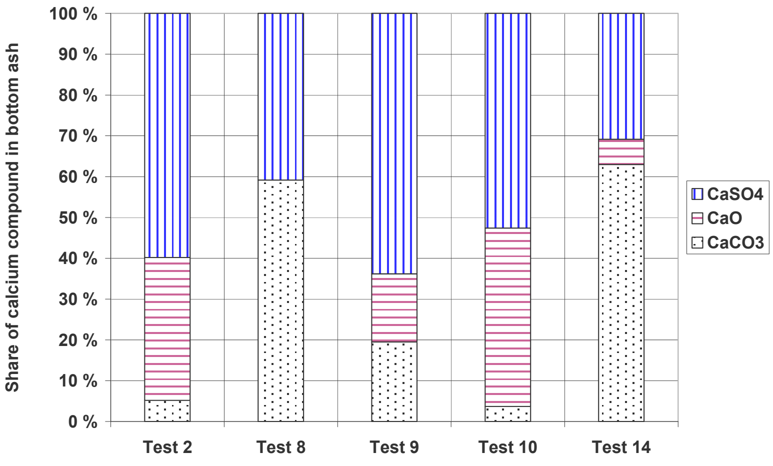

Figure 5. Share of calcium compounds in bottom ashes.

NO and N_2O emissions are presented as a function of bed temperature in Figure 6. Both emissions were clearly lower in oxygen-firing tests. NO emissions were quite independent on temperature and N_2O emissions decreased with increasing temperature in tested temperature range 780-910°C. Flue gas recycling had strong decreasing effect on NO emissions which can be seen by comparing oxygen-firing test with bottled O_2/CO_2 feed (test 14) with oxygen-firing tests flue gas recycling. That observation can be explained by reduction of recycled NO to N_2 when it passes through fluidized bed with reducing conditions in lower furnace. The same phenomenon can be seen also for N_2O emissions. NO and N_2O emissions were lower in test 14 with bottled O_2/CO_2 than in air-firing tests with comparable conditions. Possible reason for lower nitrogen oxide emissions of test 14 is that limestone was not calcinated to CaO which is known to increase the formation of NO and N_2O by catalytic effect [Lawrence et al.]. Another possible reason for lower NO and N_2O emissions of test 14 can be the gasification reaction between CO_2 and char forming CO. CO is then reducing the NO and N_2O to N_2. So it can be concluded that both flue gas recycling and high CO_2 content in oxygen-firing conditions decreases nitrogen oxides emissions. In air-firing tests higher limestone feed rate increased the NO emissions by catalytic effect of CaO as expected.

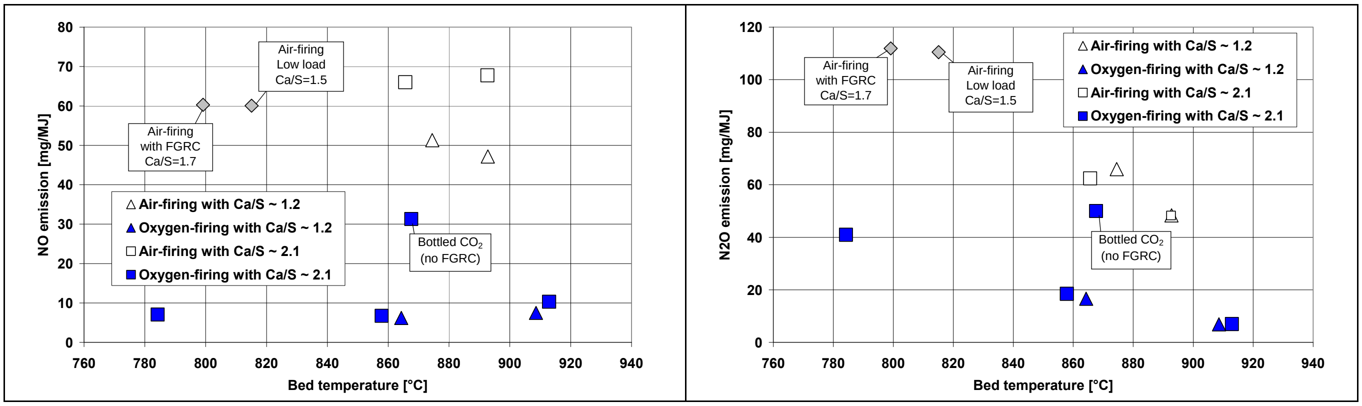

Figure 6. NO emissions (on the left) and N_2O emissions (on the right) of air- and oxygen firing tests.

1-D MODELING RESULTS

A CFB boiler thermal performance design and calculation program combined with a 1D CFB design model is used at Foster Wheeler both in calculation of mass and energy balances and in dimensioning of boiler heat surfaces, furnace and solids separator. The tools are also used for performance calculations of different load cases and fuel mixtures. The experiments done at test facilities of different scales provide information on the differences between air firing and oxy-fuel combustion, and the acquired knowledge is being incorporated in the boiler design tools. In addition the models are already being used for creating preliminary oxy-CFB boiler designs.

The stationary 1D design model is a semi-empirical tool consisting of several sub-models. The empirical correlations used in the sub-models are validated in air combustion with extensive amount of small- and full-scale measurements. However, the main flue gas compounds in oxygen-firing are CO_2 and H_2O, which change combustion and emissions formation and reduction mechanisms compared with normal combustion with air. Changes also occur for instance in the gas density, radiation properties and $CaCO_3/CaO$ equilibrium, with possible impacts on sulfur capture and particle fragmentation, with further effects on solids circulation and heat transfer, etc. The new small-scale test experimental data is being utilized in the development and validation of various sub-models also for oxygen firing conditions.

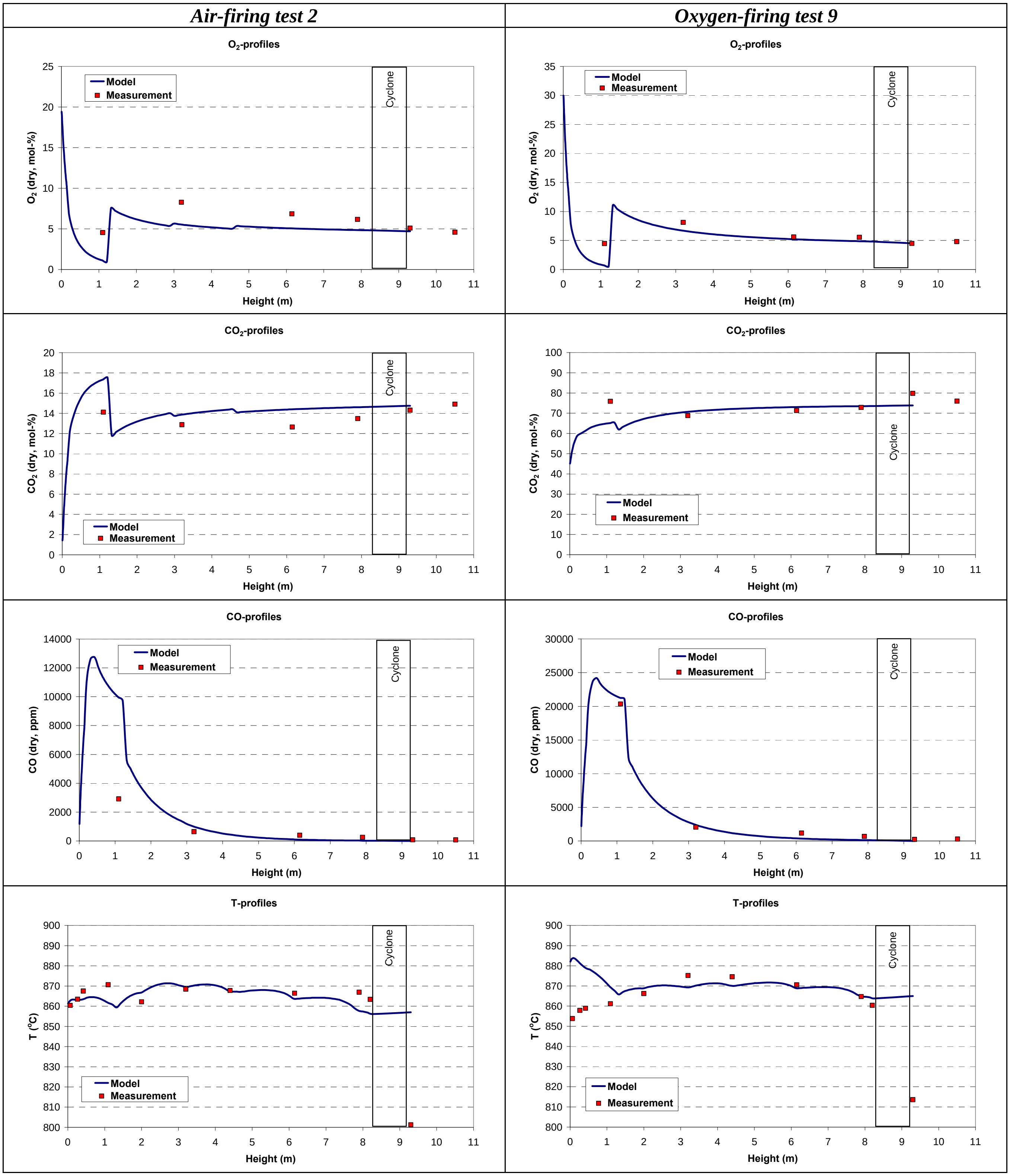

Figure 7. Modeled and measured emission and temperature profiles of air-firing test 2 and oxygen-firing test 9.

Both the air and the oxygen firing tests were calculated with the current version of the 1D design model using parameters fitted for air combustion and VTT's CFB pilot. The gas profiles (O_2, CO_2 and CO), temperature profiles, and unburned carbon in bottom and fly ashes were compared with the measured values. An example of the preliminary results from tests 2 and 9 is shown in Figure 7**Error! Reference source not found.**. The gas profiles in oxygen-firing can be modeled reasonable well with the current model. However, more info on both char reactivity and the volatile release and combustion in oxygen firing is needed. This can be seen especially from the amount of CO on the dense bed (effect of gasification), differences in the O_2 profiles and the amount of modeled unburned carbon. The sub-models will be updated with analysis results from the performed tests.

DEVELOPMENT OF FLEXI-BURN^{TM} CFB BOILER

Foster Wheeler has been developing oxy-fuel CFB combustion since 2003 through:

- Knowledge and design tool development
- Test activities (VTT's bench scale & small pilot scale CFB)
- Conceptual and feasibility studies (boiler design)

In the development of Flexi-Burn CFB boiler technology, FW in cooperation with VTT applies a similar approach that has been used in the scale-up of CFB boilers in the last two decades. Bench and pilot scale combustion test rigs provide well-controlled environments for studying of different phenomena related to combustion, heat transfer and emissions. Process understanding gained from small-scale experiments and modeling can be linked to designing of full-scale CFB boilers. Figure 8 illustrates the principle, which is currently being applied also to incorporate the specific features of oxy-fuel combustion.

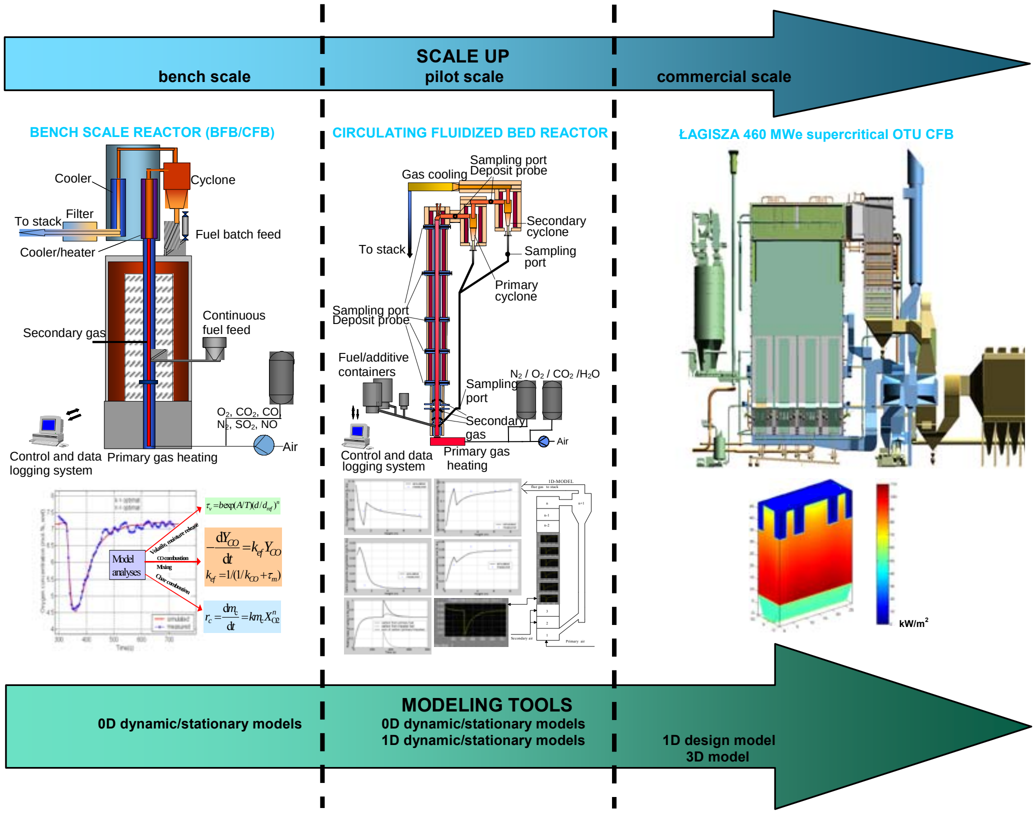

Figure 8. Scale-up approach based on integrated experimental and modeling work.

The oxy-fuel combustion process has differences when compared with conventional air combustion. With current knowledge, the behavior of a Flexi-Burn CFB boiler will in many respects be close to that of existing air-fired boilers in both operation modes. Large boilers can already be designed and performance estimated using the best available prediction methods. However, as it appears that commercialization will have to take place in much bigger steps than the realized scale-up of air-fired CFB boilers, the uncertainties in performance predictions will have to be minimized.

Reliability of performance predictions will depend on understanding the behavior of various phenomena occurring in the combustion process. Examples of such phenomena are combustion, heat transfer, mixing, gas phase reactions, emission formation and corrosion reactions. These phenomena are put together in design tools and methods, producing the required level of reliability in boiler predictions. The understanding of various phenomena is developed by planning tests and measurements to pick up the behavior of each phenomenon separately. On the other hand, the behavior of a real combustion process is a result of interactions between several phenomena. Modeling of real comprehensive process with design tools will serve as a further validation of process understanding.

CONCLUSIONS

A pilot test campaign was conducted to compare the CFB combustor performance in air and oxy-combustion operations. If oxygen level is the same in oxygen-firing and air-firing cases there should not be large differences in burning. The specific heat capacity of CO_2 is higher compared to nitrogen which causes a difference between air- and oxygen-firing. More energy is needed in oxygen-firing compared to air-firing to increase temperature in the bed area due to difference in heat capacity of CO_2 and N_2. The test data showed that if air- and oxygen-firing cases would have the same feed gas temperature, the bed of oxygen-firing case would be cooler. In addition the recirculation of the flue gas evens up the temperature profiles in oxygen-firing.

The test data indicated that sulfur capture was on the same level in air- and oxygen-firing in similar combustion conditions. In oxygen-firing conditions sulfur is captured by normal calcination-sulfation route, by direct sulfation, or by combination of these. In particle point of view sulfation is faster by calcination-sulfation route at the beginning, but with direct sulfation hard sulfate surface is not formed on the particle and in longer run the sulfur capture can be more efficient than in air-firing. Thus, the total sulfur capture depends also on residence time of limestone particles in the combustor, which depends e.g. on ash content of fuel, ash particle size and therefore bottom ash removal and separation efficiency of cyclone. High flue gas recycling rate of oxygen-firing prolongs the residence time of gas in the combustor and thereby improves sulfur capture by limestone.

Nitrogen oxide emissions were found to be clearly lower in oxygen-firing conditions than in comparable air-firing conditions. As explanation for low emissions are suggested reduction of nitrogen oxides to elementary nitrogen when flue gas is recycled through bed material with reducing conditions. Also possible reaction between CO_2 and char forming CO can enhance further reduction of nitrogen oxides. In addition to the conventional air staging typical used in air firing, oxygen-firing enables almost unlimited oxidant staging by different mixture ratios of oxygen and recycled flue gas for further minimization of nitrogen oxides.

The air- and oxygen-firing tests were calculated with the current version of the 1D CFB model using parameters fitted for air combustion and VTT's pilot. The gas profiles in oxygen-firing were modeled reasonable well with the current sub-models. More information on the differences between air and oxygen firing in solid profiles, volatile release and combustion and char reactivity will be obtained in future. The SO_2 sub-models in 1D design model will also be tested and enhanced to cover the mechanisms of oxygen-firing in the future. The 1D model will be further upgraded by validating it with test data also from larger pilot units, and by developing more accurate sub-models for combustion phenomena like char combustion and emissions.

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