Computers and Chemical Engineering 61 (2014) 203–219

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Oxidant control and air-oxy switching concepts for CFB furnace operation

Matias Hultgren[a,*], Enso Ikonen[a], Jenö Kovács[b]

[a] Systems Engineering Laboratory, University of Oulu, Linnanmaa, POB 4300, FI-90014 Oulun yliopisto, Finland
[b] Foster Wheeler Energia Oy, Relanderinkatu 2, POB 201, FI-78201 Varkaus, Finland

ARTICLE INFO

Article history:
Received 12 June 2013
Received in revised form 12 October 2013
Accepted 24 October 2013
Available online 8 November 2013

Keywords:
Power plant
Oxy combustion
CCS technology
Simulation
System dynamics
Process control

ABSTRACT

Oxy combustion in circulating fluidized bed (CFB) boilers was investigated in this paper. Oxy combustion is a carbon capture and storage technology, which uses oxygen and recirculated flue gas (RFG) instead of air as an oxidant. Air and oxy combustion were compared through physical considerations and simulations, focusing on process dynamics, transients and control. The oxidant specific heat capacity and density are elevated in oxy combustion, which leads to slower temperature dynamics. Flue gas recirculation introduces internal feedback dynamics to the process. The possibility to adjust the RFG and oxygen flows separately gives an additional degree of freedom for control. In the simulations, "direct" and "sequenced" switches between air- and oxy-firing were compared. Fast "direct" switches with simultaneous ramping of all inputs should be preferred due to the resulting smooth temperature responses. If these process input changes are unfeasible, the fuel should be altered after the gaseous flows ("sequenced" method).

1. Introduction

This paper investigates the differences between oxy combustion ("oxyfuel" process) and air combustion in circulating fluidized bed (CFB) power plants, with a particular focus on the process dynamics and transient behaviour in the oxy-CFB. Oxy combustion is one of the major industrial carbon capture and storage (CCS) technologies, which also include pre- and post-combustion capture, as well as chemical looping combustion (CLC). Carbon dioxide emissions have received an increasing attention because of the concern for climate change, especially for industrial branches consuming fossil fuels. One solution for reducing CO_2 emissions in power plants is to capture the CO_2 from flue gases with CCS. The captured and processed CO_2 is transported to underground or underwater high-pressure storage sites or, alternatively, used in industrial applications.

In oxy combustion, solid fuel is combusted with a mixture of pure oxygen and recirculated flue gas (RFG) from the process instead of air as an oxidant, resulting in a flue gas CO_2 concentration of 70–98 vol.% (dry) and thus an easier recovery of the carbon dioxide from the flue gas. Oxy combustion has been deemed as one of the most promising options for CO_2 capture, when considering the energy, cost efficiency and extremely small atmospheric CO_2 release of the process. The main structural and operational differences between air and oxy combustion plants are presented in this paper, concentrating on the dynamic aspects leading to control considerations. Even though the ultimate goal of the overall research is to develop controls for oxy-CFB, this paper deals with the general aspects and concepts of combustion control suitable for both air- and oxy-fired CFB boilers.

In fluidized bed (FB) combustion of solid fuels, fuel particles are fluidized and combusted in a bed of incombustible material of e.g. sand or ash in the furnace riser. The fluidizing medium is the primary input gas flow, which commonly contains the oxidizing agent needed for combustion. In circulating fluidized beds (CFBs), a sufficiently high gas velocity and small particle size enable the solids to become entrained with the bed and to leave the furnace riser tube. The solids are separated from the flue gas in a gas–solid separator, from which the flue gas continues to the backpass and the solids are recycled back to the bed through the solids circulation system. Together, these process components form the hotloop (Fig. 1), which is the studied CFB boiler subsystem of this paper. CFB combustion is used for solid fuels and also for liquid fuels to some extent.

When designing control solutions for CFB combustion, the main issues affecting both the steady-state and dynamic behaviour of the process can be summarized with the key points below:

• Fluidization

As the furnace input gas (oxidant) flows are responsible for the fluidization in the CFB, any effects the oxy-firing process

* Corresponding author. Tel.: +358 503502923; fax: +358 85532304.
E-mail addresses: matias.hultgren@oulu.fi (M. Hultgren), enso.ikonen@oulu.fi (E. Ikonen), jeno.kovacs@fwfin.fwc.com (J. Kovács).

0098-1354/$ – see front matter
http://dx.doi.org/10.1016/j.compchemeng.2013.10.018

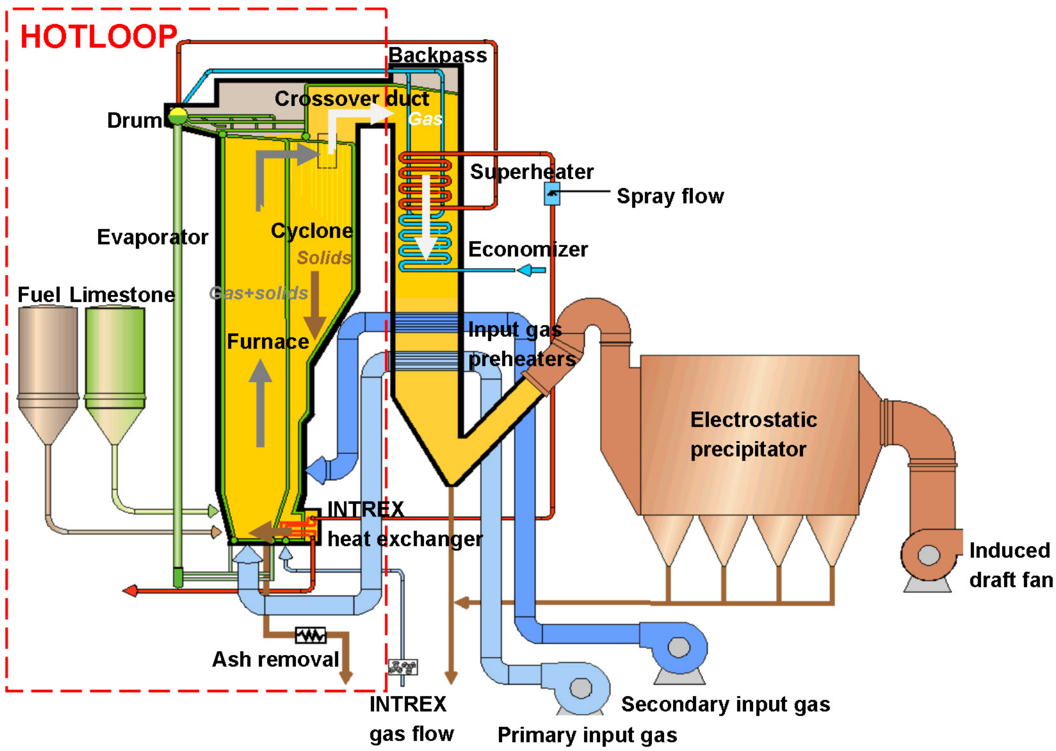

Fig. 1. Operation schematic of the CFB boiler, with the hotloop highlighted with the dashed line. Modified from Foster Wheeler Energia Oy (2012).

configuration has on the gas flows have the potential to alter the fluidization and thus the mixing and heat transfer in the bed. Proper fluidization has to be maintained in the bed.

- Input oxidant flows, i.e. input gas flows

The oxidant flow is air for air-fired FB processes and oxygen + recirculated flue gas for oxy combustion. This is the main cause for the differences between air and oxy combustion. The heat capacity, density and chemical component concentrations of the oxidant are directly related to the differences between the combustion atmospheres. For the combustion dynamics, especially the oxygen input and thus the oxidant O_2 percentage are of importance.

- Heat transfer & boiler MW output

The heat transfer in the dense bed, the upper furnace, the flue gas path and the return leg affects the selection of heat exchanger sizes and the power plant performance optimization. The differences in heat transfer between air and oxy combustion are thus significant factors for combustion control. Maintaining a correct heat transfer distribution is especially important for once-through (OTU) boilers, as these units don't contain a water-steam drum as a buffer for steam generation.

- Combustion & firing power

The combustion in the CFB furnace riser determines the generated amount of heat in the boiler. When comparing air and oxy combustion, the effect of the atmosphere change on the combustion reactions and the heat generation has to be considered. Important process variables are furnace temperatures at different points in the riser and the flue gas O_2 content.

- Combustion-related reactions

Because of the flue gas recirculation and absence of air in oxy combustion, the concentrations of emission components such as SO_x, NO_x and CO will be affected by the combustion mode. This has the potential to cause changes in the gaseous emissions of power generation, as well as in the mechanisms and balances of emission formation reactions.

- Fuel

The fuel input determines the combustion progression and the emission formation. Knowledge of fuel flow properties such as heating values, carbon and moisture contents, solids/volatiles distributions, as well as mass flow accuracies can be used in feed-forward and model-based control solutions. As the fuel flow is set separately from the input gas flows, no notable differences between air and oxy combustion should occur because of the fuel alone.

- Integration of the boiler and supporting units

In oxy combustion, the boiler island depends on the oxygen production and CO_2 post-processing units. As a result, coordinated or plant-wide boiler island control might be of importance. The O_2 is produced with an air separation unit (ASU), while the CO_2 is captured using carbon compression (CCU) and purification (CPU) units. Dynamic properties such as production rates, startup times and load following capabilities of these units need to be considered in the overall control design.

- Water-steam cycle

The water-steam cycle contains the main power plant control loops, such as live steam temperature control, boiler-turbine unit control, feedwater control and drum level control. As the heat used on the water-steam side comes from the combustion and as the main focus of this work was on hotloop dynamics, the water-steam control issues in oxy-firing boilers were not discussed in this paper.

- Boiler island in grid control

Special requirements arise, when the boiler participates in grid frequency or district heating network control. As the focus of this paper was on the CFB hotloop, these matters were not discussed here.

Currently oxy combustion is in its pilot testing and early commercialization stage. Both theoretical and experimental research is being conducted on the CCS process chain by universities and companies in the field. For example, six demonstration projects are supported by the European Energy Programme for Recovery (EEPR 2010–2013), with the aim of making CCS zero emission power generation commercially feasible by the year 2020. One of these projects is the planned CCS supercritical CFB Compostilla project in Spain. The necessary technology for this process is currently being tested at the same location with the CIUDEN 30MW oxy combustion and CCS test facility. From large-scale general CCS investigations, the "Special Report on Carbon Dioxide Capture and Storage" report by the IPCC (IPCC, 2005) is one of the most extensive and it includes a section on oxy combustion. Aside from solid fuel combustion, oxy combustion is being researched for other power generation systems like natural gas burners and gas turbine cycles (e.g. Hasegawa, 2013; Thorbergsson, 2012; Yin, Rosendahl, & Kaer, 2011).

So far, oxyfuel research has mostly considered steady-state process conditions and the pulverized coal (PC) oxy-coal process. Although this paper focuses on the fluidized bed combustion technology, oxy-PC research results offer valuable insights into the general differences between air- and oxy-firing. Toftegaard, Brix, Jensen, Glarborg, and Jensen (2010) combined a wide array of oxyfuel PC references into an extensive review article focusing on the differences between air and oxy combustion. Davidson and Santos (2010) also reported on pulverized fuel oxy combustion and the overall development of the oxy-firing technology. Wall et al. (2009) focused on fuel reactivity, combustion characteristics, heat transfer and emission formation in oxy-PC.

Despite the usefulness of the oxy-PC research results, the CFB has its own requirements and thus calls for specific CFB references. In general, the fluidized bed technology has been widely documented in the literature; see e.g. Basu (2006). For oxy-CFB, Czakiert et al. concentrated on combustion kinetics and conversion rates of different fuel components (Czakiert & Nowak, 2010; Czakiert, Bis, Muskala, & Nowak, 2006; Czakiert, Sztekler, Karski, Markiewicz, & Nowak, 2010). Duan, Zhao, Zhou, Chengrui, and Chen (2011) presented results from 50 kW_{th} pilot oxy-CFB measurements. The particular focus of these authors was on the input oxidant O_2 percentage and its effects on the differences between air and oxy combustion. Practical design issues were considered by Romeo et al. (2011). Oxy-CFB research from Foster Wheeler was presented e.g. by Eriksson et al. (2007) and Hack et al. (2008), who described the air/oxy Flexi-Burn^{TM} technology, oxy modelling studies, pilot and bench scale experiments and conceptual oxyfuel retrofit designs. E.g. Suraniti, ya Nsakala, and Darling (2009) and ya Nsakala et al. (2004) discussed the oxy-CFB research work and experimental testing of Alstom Power.

Few papers related to oxyfuel control design have been published up to date, for oxy-CFB in particular. Oxy combustion results in several changes in the operation of the process which require attention during boiler control design. Due to a different composition of the combustion atmosphere, the furnace temperature and heat transfer dynamics will become slower. In addition, the flue gas recirculation in oxy mode introduces internal feedback dynamics to the system, a feature not found in basic air combustion (without flue gas recirculation). As modern fossil fuel power plants (including oxyfuel plants) have to be able to provide fast responses to load changes, careful control design is needed. For oxy combustion, switches between air and oxy mode are also an essential part of e.g. the startup and shutdown sequences of the plant. Some references about air-oxy-air switches can be found in the literature (e.g. McDonald & Zadiraka, 2007; Weigl, 2009). The separate oxygen and RFG gas flow inputs in oxy combustion give more degrees of freedom for performing combustion control. The investigation of the specific features of oxy-CFB dynamics and the combustion control challenges related to the technology form the motivation for this paper.

Table 1
The properties of the fuels that were used in the simulation tests.

Components	Spanish anthracite	Petcoke
Ultimate analysis (wt%, dry)		
C	55.2	86.4
H	2.2	3.9
N	0.8	1.7
O	4.4	1.8
S	1.8	5.7
Proximate analysis (wt%)		
Moisture	12.1	3.1
Ash (dry basis)	35.6	0.4
Volatiles (dry basis)	10.2	12.8
Heat value (MJ/kg)		
LHV (as received)	20.3	34.5

After this introduction, the process model used in this paper and its background experimental research are presented in Section 2. Section 3 deals with oxyfuel static aspects and the steady-state differences between air and oxy combustion in order to form a background for understanding oxy-firing process dynamics. Section 4 discusses the main differences in the process dynamics of oxy and air combustion and presents the challenges and possibilities in the oxy-CFB hotloop control structure. The dynamic simulations of this work are discussed in Section 5 through switching tests between air and oxy combustion. Section 6 summarizes the conclusions of this work.

2. Experimental setup

A dynamic 1-D Matlab/Simulink hotloop model was used to investigate the dynamics of the oxy-CFB process. This model has been developed in cooperation between Foster Wheeler Energia Oy, the Lappeenranta University of Technology (LUT) and the University of Oulu. A description of the model can be found in Ritvanen et al. (2012). The hotloop model structure had been previously validated and used extensively for various air-fired circulating fluidized bed boilers of different sizes. In the preparation work for this paper, a successful initial model validation in oxy mode was performed using measurement data from an air/oxy-fired pilot combustor (Tourunen, 2010) with a fuel power of 50–100 kW_{th} in oxy mode and 20–50 kW_{th} in air mode. The pilot contained a furnace tube (height 8 m, inner diameter 167 mm), a solid material circulation tube, cyclones for solids and fly ash separation, flue gas processing equipment, a flue gas recirculation system, as well as fuel, limestone and oxidant feeding lines. In the testing campaign, a fuel blend with an approximate 70/30 mass percentage ratio of anthracite (primary fuel) and petcoke (secondary fuel) was burned (Table 1). To form the oxyfuel oxidant, RFG from the flue gas line was mixed with room temperature high purity bottled O_2, resulting in a realistic oxy-firing process configuration. The primary oxidant was introduced through the grid with primary air preheating for air mode, while the secondary oxidant was fed from three different levels in the riser.

The model validation was conducted through air/oxy load steps and oxy load ramps, using filtered actual input data from the pilot.

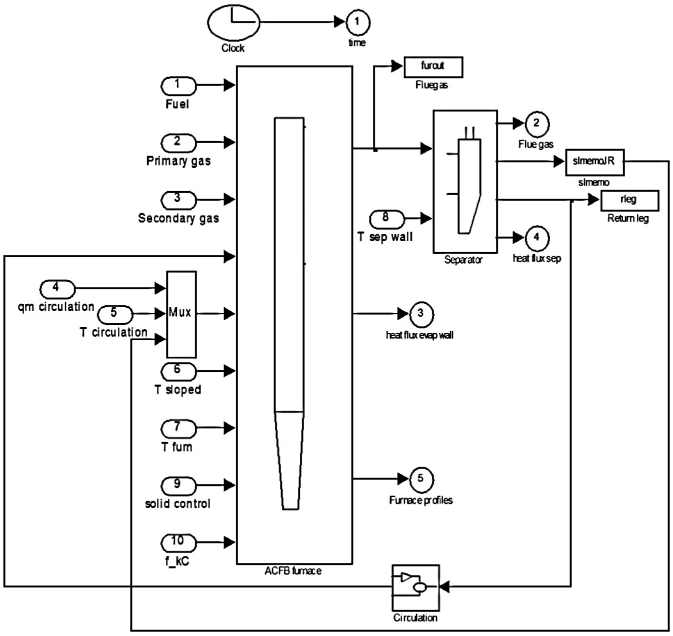

Fig. 2. The hotloop module of the air/oxy dynamic model used in this study.

For the measurement campaign, the pilot was equipped with extensive temperature, heat transfer, pressure, solid material sampling and flue gas composition measurements. The input data included RFG, pure O_2 and air mass flows, fuel silo weight measurements and fuel feeding screw RPM values, as well as primary and secondary oxidant temperatures. The calculation of fuel mass flows was based on least squares fits from fuel silo weight decreases with minor modifications based on alternations in the process outputs. Output measurements used in the validation mainly contained flue gas composition data and furnace temperatures.

For this paper, separate air-oxy-air switch test simulations were conducted with the hotloop model. Like the validation cases, the model was configured according to the pilot plant and thus only contained the furnace, the gas–solid separator and the solids circulation system. These subsystems were included in the hotloop Simulink model (Fig. 2), while the calculation codes of the furnace and the separator had been implemented as C-coded s-functions. For oxy-firing simulations, a separate input gas mixing module for mixing the RFG, pure O_2 and air flows to form the primary and secondary oxidants was also included into the simulator. A pure O_2 flow purity of 96.6 wt% was used for all simulations in this study, with the rest of the pure O_2 consisting of nitrogen.

The CFB process was modelled using both physical and empirical approaches. The furnace riser tube consisted of 20 ideally mixed calculation elements, for which element specific mass and energy balances were solved against time with an ODE solver. A combined energy equation for the gaseous and solid phases was defined to solve the element temperatures, while the hydrodynamics, combustion characteristics, vertical density profile and heat transfer inside the modules were calculated using empirical and semi-empirical correlations. The heterogeneous reactions of carbon, hydrogen and sulphur were considered for the solid fuel combustion. Hotloop cooling could be applied through element-specific surface temperature parameters to simulate the effects of the water-steam cycle. Although the model contained no water-steam side calculations, it is usually used as the hotloop component in a complete power plant simulation software application.

The number of hotloop model system states depended on the process configuration and the inputs. For this paper, 855 states in total were used. Because of the large amount of states, the model is mainly a simulator for investigating process dynamics and testing control solutions, and should not be applied directly in e.g. model-based control. Nevertheless, a state estimation approach for model-based analysis of an experiment campaign has also been developed (Ikonen, Kovács, & Ritvanen, 2013). An input–output "black box" structure of the model is illustrated in Fig. 3.

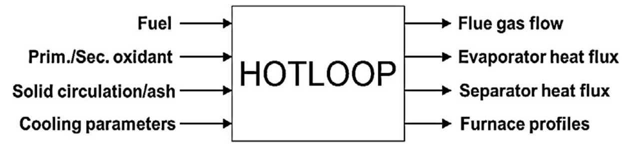

Fig. 3. Simplified input–output structure of the hotloop model.

3. Oxy-CFB combustion, static aspects

The static aspects of oxy combustion need to be considered before investigating, how oxy process dynamics will differ from air-firing. This chapter presents the oxyfuel-related changes in the CFB operation that lead to steady-state differences in heat transfer, fluidization, combustion and emission formation. Furthermore, the additional process units needed for oxy combustion are discussed.

3.1. Recirculated flue gas

Replacing the input air with oxygen and recirculated flue gas (RFG) is the source for the various differences between air and oxy combustion, although the basic operational principle of solid fuel combustion remains the same in both combustion modes. In the oxy-CFB, pure oxygen is required for the combustion, while RFG serves as the main fluidizing medium. The RFG is essential for the fluidization, as the pure O_2 volumetric flow rate is much smaller than the corresponding amount of input air. The other main functions of the RFG are to act as a heat transporting medium and to bring furnace temperatures to the optimal operating regions (typically 850–900 °C in CFB) of combustion, heat transfer and bed sulphur capture. It is important to acknowledge that the cooling and fluidizing effects of the RFG are opposite: an RFG-based increase in fluidization simultaneously contributes to lowering the furnace temperatures. This is different from air-firing, as an increase in the air input automatically leads to an increased O_2 input, as well. As the RFG is extracted from the flue gas, the exhaust gas heat loss will be smaller in oxy mode than in air mode.

A flue gas recirculation system with mixers for mixing oxygen, RFG and also air during combustion mode switches is mandatory for the oxy-firing operation. Even though flue gas recirculation can also be used in air-fired boilers for e.g. temperature control, the RFG is the main component of the input oxidant in oxy combustion. The flue gas recirculation system can be designed in various ways, mainly involving the choice of the RFG withdrawal point from the flue gas line and the operations performed to the recycled flue gas. The chosen recirculation point affects the RFG composition and thus the properties of the process input oxidant, as well as the size, energy and material requirements of flue gas and RFG processing units. Choosing between a wet and a dry flue gas recycle is especially important (Toftegaard et al., 2010; Eriksson et al., 2007). Air leakage into the boiler also needs to be dealt with in the process chain, as the CO_2 product quickly becomes diluted by nitrogen and the CO_2 separation difficulty is increased, if air leakage into the oxyfuel boiler is extensive.

Due to the oxy-firing process configuration, the concentrations of gaseous components in the oxidant and the flue gas become markedly different from air combustion (Table 2). Especially the remarkable increases in CO_2 and H_2O and the reduction in N_2 should be noted here. As the specific heat capacities of both CO_2

Table 2
Typical concentrations of gaseous components in the oxidant and the flue gas before water condensing in air and oxy combustion.

		Percentage vol.% in gas (wet basis)	
		Air combustion	Oxy combustion
Input oxidant gas	O_2	21	21–30
	N_2	79	0–10
	CO_2	0	40–50
	H_2O	Small	10–20
	NO_x, SO_x	No	Yes
Flue gas	O_2	3–4	3–4
	N_2	70–75	0–10
	CO_2	12–14	60–70
	H_2O	10–15	20–25
	NO_x, SO_x	Yes	Yes

Data from Davidson and Santos (2010).

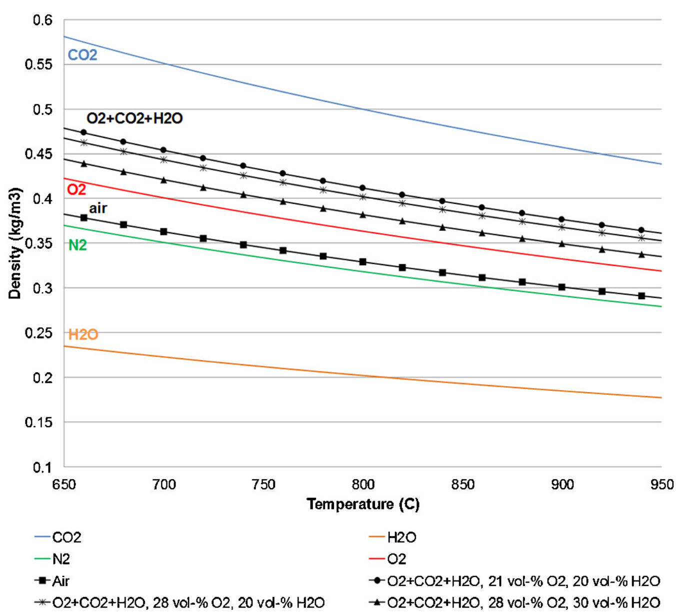

Fig. 4. Density values for various gaseous components and mixtures at 1 atm and different temperatures, when the ideal gas assumption is used for non-water species.

and H_2O are higher than that of N_2 (Table 3) in the boiler temperature range, the heat capacities of the gaseous flows in the CFB will increase in oxy combustion. CO_2 also has a larger molecular weight and density than nitrogen (Fig. 4), resulting in a higher oxyfuel oxidant gas density than the density of air. Therefore, if the nitrogen of air is simply replaced with RFG and the total input gas mass flow is kept constant, the oxidant gas volume flow will be smaller in oxy mode than in air mode, which causes a change in the fluidization conditions. Like in air combustion, the steady-state composition and thus the physical/chemical properties of the oxyfuel flue gas flow will depend on the input fuel feed properties. However, the flue gas recirculation in oxy mode will also link the oxidant composition to the fuel flow in the oxy-CFB.

3.2. Heat transfer distribution

The oxyfuel oxidant heat capacity and density elevations mean that furnace temperatures will be lowered, if the heating power or furnace cooling in oxy mode remains unchanged from air mode. As the oxidant O_2 contents of Table 2 and research literature indicate, the lower temperature levels can be prevented by oxidant O_2 enrichment, i.e. by controlling the mixing ratio of pure oxygen and RFG to increase the oxidant O_2 content above the 21 vol.% value of air. The O_2 percentage required for air-like furnace temperatures depends on several factors, most notably the fuel type and the flue gas recirculation system. The oxidant O_2 enrichment issue is elaborated on in Section 3.4.

Since the gas flow through the boiler would not give up heat as willingly in oxy combustion as in air combustion due to its elevated heat capacity, combustion heat is transported further downstream in oxy mode and the heat distribution between heat exchangers might be affected. In general, the conduction of heat further downstream in the process chain contributes towards an improved convective heat transfer, while the radiative heat transfer close to the furnace decreases. Indeed, improved heat transfer efficiencies at least in the convective section of the boiler have been reported by e.g. Hack et al. (2008) and IPCC (2005).

Despite the heat capacity elevation, it is difficult to make conclusions about the overall heat transfer differences between air- and oxy-firing, as heat transfer is influenced by multiple factors. For convective heat transfer, these include the fluid dynamics of the system and thus the fluidization (e.g. Reynolds and Prandtl numbers), the heat conductivity of the gas and the gas temperatures of the superheaters (Toftegaard et al., 2010). Moreover, the main gaseous components of oxy combustion (CO_2 and H_2O) are radiative species, unlike N_2 in air combustion. This, along with possible furnace temperature or particle size distribution effects, has the potential to boost oxy mode radiative heat transfer. Radiative heat transfer is also not as crucial for the CFB as convective heat transfer (Romeo et al., 2011). Although the oxy heat transfer is thus going to be case specific, a potential shift in heat exchanger duties should not be overlooked, as it might affect the operational points of process subsystems and bring models used in control outside their validity regions.

3.3. Combustion and emissions

A basic point of comparison between air and oxy mode is how the gaseous atmosphere affects the combustion reactions. The combustion progression is determined by the combustion reaction rate and the oxygen diffusion rate to the particle surface. Basically, the diffusivity of both oxygen and small hydrocarbons is lower in a CO_2-based medium than in an N_2 atmosphere (Toftegaard et al., 2010; Wall et al., 2009). As a result, oxygen will be less available for combustion and the volatile consumption rate will be hindered. If

Table 3
Experimental values of gaseous species at 1123 °C.

Quantity	Unit	Species				CO_2/N_2 property ratio
		H_2O	O_2	N_2	CO_2	
Density (ρ)	kg/m^3	0.157	0.278	0.244	0.383	1.6
Specific heat capacity (c_p)	kJ/kmol K	45.67	36.08	34.18	57.83	1.7
Specific heat capacity (c_p)	kJ/kg K	2.53	1.00	1.22	1.31	1.1
Heat sink (ρc_p)	kJ/m^3 K	0.397	0.278	0.298	0.502	1.7
Mass diffusivity of O_2 (D_{O2}/species)	m^2/s	–	–	1.70E−04	1.30E−04	0.8

Data from Toftegaard et al. (2010).

the oxidant O_2 content is thus kept at 21 vol.% in oxy mode, the combustion reactions will slow down, the particle heat generation rate decrease and the amount of unburned carbon potentially increase because of the diffusivity change and the lowered oxy-firing furnace temperatures. However, with oxidant O_2 enrichment, the oxygen partial pressure in the furnace will be larger than in air-firing and the temperatures will increase, resulting in raised combustion efficiency, reaction rate and char burnout levels (Duan et al., 2011; Czakiert et al., 2006), although the burnout depends heavily on the fuel type, as well. Furthermore, carbon gasification increases in oxy-firing due to the high CO_2 and H_2O contents in the gas.

The formation of emission components will be affected by the flue gas recirculation and the changes in reaction mechanisms. Due to the accelerated fuel gasification, the formation of CO will be larger in oxy-firing than in air-firing, although the formed extra CO will probably be consumed before leaving the furnace (Duan et al., 2011). Due to the lack of elemental nitrogen from air and through several specific reaction mechanisms, NO_x formation can be minimized in oxy combustion (Toftegaard et al., 2010). The absolute amount of char and ash will stay approximately similar for both combustion modes, while the size distribution of the solids might be altered e.g. by changes in furnace temperatures. So far, bed agglomeration, slagging and fouling have not presented any significant problems for oxy combustion in FB boilers.

In fluidized bed limestone sulphur capture, the CO_2 partial pressure and furnace temperature changes in oxy combustion have the potential to alter the predominant sulphation reaction mechanism from indirect (first calcinated, then sulphated) to direct sulphation (Toftegaard et al., 2010). The overall differences between the air and oxy combustion sulphur capture efficiencies are debated upon. Additional oxyfuel process requirements come from the possibility of limestone recarbonation into $CaCO_3$ and from locally elevated concentrations of acidic SO_x gaseous species.

3.4. Oxyfuel boiler configuration

Because of the different air and oxy combustion oxidant and flue gas compositions, existing air-fired boiler designs would not necessarily be optimal for oxy-firing from a heat transfer, fluidization or combustion perspective. Therefore, it should be defined whether the goal of the design is an oxyfuel retrofit of an existing boiler or an oxyfuel greenfield plant optimized mainly for oxy combustion. The target of oxy retrofits is to obtain air-like combustion conditions in the furnace, as the structure of the oxyfuel power plant will then differ from air-fired plants with slight modifications only.

In order to produce similar furnace temperatures and temperature profiles to air-firing in oxy combustion, oxidant O_2 enrichment is needed. In principle, the O_2 content of the oxidant and the furnace temperatures can be increased either by primarily reducing the cooling RFG flow or by raising the firing power by increasing the pure oxygen input. Consequently, the latter option results in a simultaneous increase in the fuel flow and thus a greater heat generation through combustion. Both of these methods have their own disadvantages: a smaller RFG flow leads to a smaller input gas volume flow (RFG is the main gas component) and might thus hamper the fluidization in the bed, while increasing the pure O_2 input flow results in higher oxygen production costs. However, as proper fluidization has to be ensured at all times in the CFB, the temperature target will most likely mainly be achieved by increasing the pure O_2 flow and firing more fuel (Hack et al., 2008).

In oxy greenfield plants with no restrictions from air combustion compatibility, the oxidant O_2 percentage can be raised well beyond the values required for air-like combustion conditions, leading to higher temperatures, smaller entropy losses and potentially a more efficient combustion with better char burnout and a smaller oxygen excess. If the RFG flow can be reduced to achieve this, the gas flows and total gas volume in the system will be reduced compared to air-fired boilers, resulting in smaller oxy power plants with an unaltered firing power. This will lead to reduced construction costs, thermal radiation heat losses and flue gas recirculation power requirements. Because of the risks associated with new technologies like oxy combustion with high oxidant O_2 levels, the first generation of oxyfuel boilers is likely to consist of modifications of existing air-fired units.

The notions presented for retrofits can, to some extent, be applied to dual-firing and oxy-ready boilers, which strive for the process to function well in both air and oxy mode. Beside new technology risk mitigation, these solutions offer operational flexibility regarding the power demand and the prices of emission rights. The Foster Wheeler Flexi-Burn™ boiler (Fig. 5) is one example of a flexible air/oxy boiler technology. As both air- and oxy-firing are used, switches between air and oxy combustion and also between different oxy-firing oxidant O_2 percentages are an integral part of the operation. Air-firing is also used in retrofits during startups and shutdowns of the boiler.

3.5. ASU, CCU and CPU

On a plant-wide scale, the major differences between air and oxy combustion come from the oxy-firing pre- and post-processing units, namely the ASU, CCU and CPU. The necessary processing steps and product quality requirements in the carbon compression and purification units (CCU + CPU) are largely determined by the uses and storage methods of the CO_2. The CCS flue gas processing will at least require a stage-wise compression of the gas to high or even supercritical pressures, dehydration, cooling and non-condensable species removal. The input oxygen is usually produced with one or

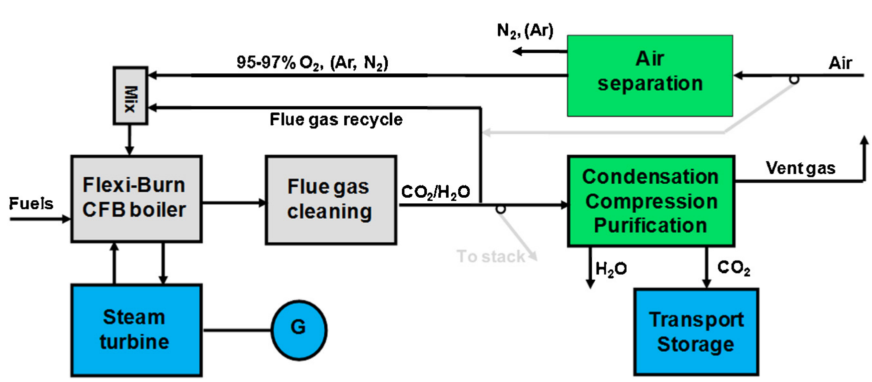

Fig. 5. Schematic of a Flexi-Burn™ CFB power plant (Foster Wheeler Energia Oy, 2012).

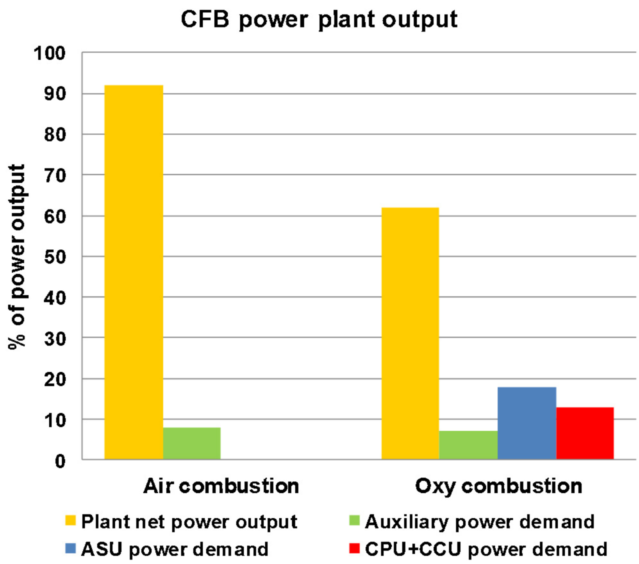

Fig. 6. Air/oxy-CFB output power distribution example.
Data from ya Nsakala et al. (2004).

several parallel air separation units (ASU), which will typically be based on cryogenic distillation of air, when considering the current industrial scale O_2 production options.

The ASU, CCU and CPU are perhaps the most important challenge of the oxyfuel development, as the high pressures and low temperatures in oxygen production and CO_2 compression require a lot of energy and thus have a negative effect on the power plant net efficiency (Fig. 6). This applies especially to the ASU, which might cause the power plant efficiency to drop 7–9% and be responsible for 60% of the additional energy requirement of CCS (Toftegaard et al., 2010). The operating costs of the ASU, CCU and CPU are influenced by the purity of the produced oxygen and the RFG withdrawal point in the flue gas line, forming an optimization problem between air separation and post-processing costs. The oxygen production limitations in the ASU might also restrict the performance of the boiler, as current air separation solutions are only able to reach a load range of 60–100% and a maximum ramp rate of 3%/min (Toftegaard et al., 2010). The startup time of the ASU also needs to be considered.

4. Dynamic aspects and control: differences between air and oxy combustion

The main differences in the process dynamics and control of air and oxy combustion can be examined from three different angles. Firstly, the altered gaseous atmosphere composition affects the heat transfer, combustion reactions and emission formation in the bed. Secondly, the flue gas recirculation introduces dynamic aspects to the process, which need to be considered in oxy combustion control. Thirdly, the possibility to adjust the input oxygen and RFG flows separately gives an additional degree of freedom for process control. These differences present challenges and possibilities for the oxy-CFB control and will be discussed in detail in this section.

4.1. Oxidant and combustion atmosphere

The most important effect of the oxidant and flue gas compositions on the oxy-CFB dynamics are derived from the increases in gas specific heat capacity and density in oxy mode. The elevated heat capacity will cause the gas flow inside the oxyfuel boiler to heat up and cool down more slowly than in air combustion, resulting in slower temperature transients and thus slower process responses

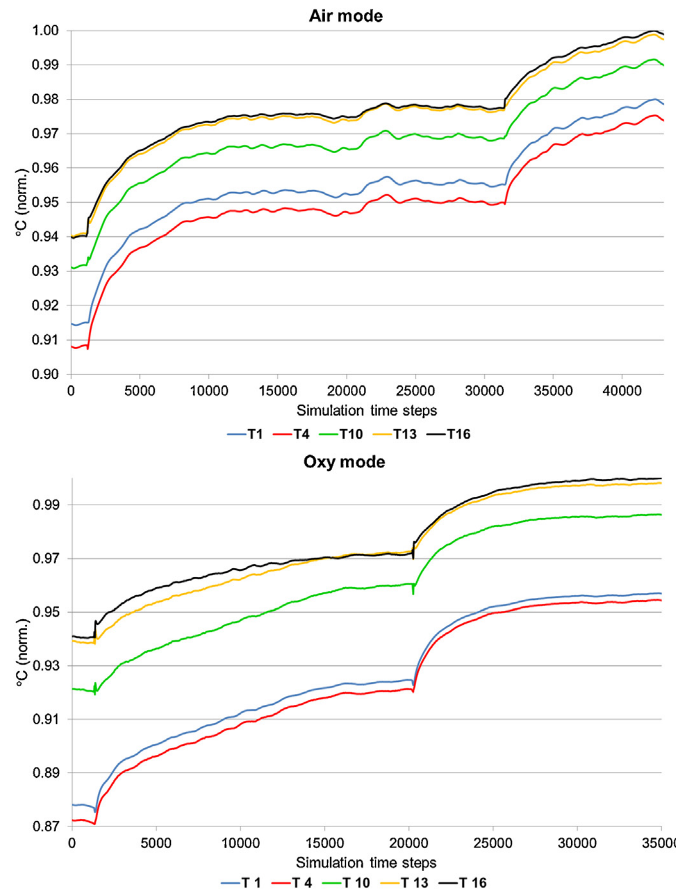

Fig. 7. Normalized furnace temperature responses at different riser heights (T) of air combustion (upper) and oxy combustion (lower) load step simulations, hotloop model validation simulations.

to load changes. The slower oxy-firing transients are demonstrated in the load step simulations of Fig. 7. As the furnace temperatures are directly connected to the heat transfer and water-steam cycle of the power plant, the indicated changes will most likely be visible in the time constants and settling times of the process MW responses, as well. The slower temperature dynamics can be considered as a disadvantage for the load following capabilities of oxy control and special attention should be paid to the selection of the combustion control structure, as the slower dynamics might have to be compensated with adjustments to the furnace cooling or fuel firing power.

The effect of the oxidant gas density on fluidization is a point of concern in the oxy-CFB switching control. The oxidant density increase in oxy mode presents an optimization problem between the particle residence time and the fluidization efficiency. As indicated in Fig. 4, the gas densities in air and oxy mode will also respond differently to temperature changes. The oxidant density effects can be summarized with the following points:

- If the oxidant mass flow is kept constant during a switch from air to oxy combustion, the gas volume flow will decrease due to its elevated oxy mode density. This means that without sufficient control measures the velocity of the fluidizing gas will decrease, which will hamper the fluidization in the bed by decreasing the turbulence and the mixing efficiency of solids. However, the smaller gas velocity will also contribute to a longer residence time of solids and thus potentially even to a better burnout.
- If the gas volume flow is kept constant during the air to oxy switch by adjusting the RFG and pure O_2 feeds to compensate for the gas

density increase, a denser oxyfuel oxidant with a similar velocity to a corresponding air flow will be able to carry solids better in the riser and improve fluidization. Similarly, this mode of operation could lead to smaller residence times and larger solids circulation amounts, as well as larger pressure difference requirements and thus an increased energy demand of the input gas feeding equipment.

In practice, the best way to run the switches will most likely be to maintain a constant gas volume flow at least for the primary oxidant in order to ensure a proper fluidization throughout the switch. Furthermore, the residence time of the fuel will have a small importance in the CFB because of the solids circulation in the hotloop. The overall effect of the oxidant on the residence time also does not seem to be straightforward and contradictory results have been presented in the literature.

The changes in the oxidant properties affect the oxy-CFB process dynamics and should be considered in its control design, as measurement and control components might need to compensate for the property differences. The task is especially problematic during load and combustion mode transitions due to the alternating gaseous component concentrations. This could lead to an adaptive control system, a lookup-table based feedforward solution or even online calculations. The effects of oxy-firing on heat transfer and fluidization depend on the fuel feed properties (see Section 3.1). However, as the dominating effect is caused by the elevated CO_2 and H_2O contents in the gaseous flows, the fuel type considerations can be omitted in this context from a process dynamics point of view. Compared to air-firing, the gas property changes also call for additional strategies for selecting the level of oxidant O_2 enrichment, handling possible heat transfer distribution changes in the steam generation and ensuring proper fluidization at all times. The special requirements of oxy-firing become especially apparent for retrofits, which are based on air-like combustion conditions.

4.2. *Flue gas recirculation*

The dynamics of the flue gas recirculation mainly concern oxidant and flue gas component concentrations, although gas compositions are also related to other furnace properties, as described in the previous chapters. The RFG is a combustion reaction product of the process and because it is also the main component of the oxyfuel oxidant, the fluidization and heat transfer are more linked to the combustion in an oxy-CFB than in air-firing. However, at the same time the degree of fluidization greatly affects the combustion and heat transfer in the boiler. This kind of a cause-effect relation introduces new dynamic aspects to the oxy-CFB process. As the recirculation links the oxidant to the fuel feed properties, variations in the fuel quality will cause different responses in the furnace outputs compared to air combustion. Apart from the recirculation itself, additional features to the total process dynamics might be presented by O_2/RFG/air mixers.

For control engineering, the most crucial flue gas component is oxygen, as the flue gas O_2 contains information about the combustion in the furnace. Because of the flue gas recirculation in oxy combustion, the total oxygen input is a combination of pure O_2 from the ASU and RFG O_2 from the flue gas. However, at low frequencies the actual oxygen demand of the process is unaffected by the recycled oxygen, as the required O_2 amount is determined by the corresponding fuel flow and the set O_2 excess. The hotloop and the RFG system can be viewed as a combined process, in which the flue gas recirculation is an internal circulation of gaseous components in the CFB furnace. Consequently, the required O_2 amount is determined by the mass balance of this system.

Like the flue gas O_2, the steady-state values of other flue gas components are not affected by flue gas recirculation, as indicated by the RFG step simulations of Fig. 8. This is dictated by the input–output mass balances of the system. However, the recirculation amount and the changes in the RFG have an effect on the flue gas composition dynamics, for example on the settling times of flue gas composition responses (Fig. 9). From these viewpoints, the flue gas recirculation system once more has analogies with an inner circulation, although the gases in the RFG line are not in active contact with the solid bed. It should be noted that the steady-state compositions remain constant with different RFG amounts only when no flue gas components are removed outside the mass balance boundary as a result of RFG processing. In Fig. 8, this was observed to a minor degree due to SO_2 removal from the RFG. The RFG amount might thus become significant for oxy-firing steady-states, if e.g. H_2O is removed from the RFG line in a dry flue gas recirculation.

The feedback nature of flue gas recirculation will cause both additional flue gas composition dynamics and larger time constants during load or process operation changes. Furthermore, the delay of the firing system will increase, as a change in the combustion reactions will not immediately be visible in the input oxidant composition. The distance of the flue gas recirculation point from the furnace thus not only influences the flue gas processing requirements, but also the process time delay for combustion-related changes. In general, controlling oxidant properties is difficult in oxy-firing, because changes in the combustion or fuel quality will also have an indirect effect on the oxidant quality. This has the potential to cause accumulation or even stability issues for the combustion, if controlled poorly.

The delay and dynamics of flue gas recirculation become visible during air-oxy-air switches, in particular. Based on the results of Weigl (2009), the most important changes in flue gas component concentrations during a switch seem to occur only after the actual switch or during the last stages of the transition ramps of air, pure O_2 and RFG, forming an s-shaped figure in the concentrations. This would suggest that special attention should be paid to the last stages of the transitions and that quick gas flow ramps would be useful in order to obtain the full oxy combustion steady-states as quickly as possible.

Unlike the switch dynamics, hotloop model load test validation simulations showed no major effects related to flue gas recirculation for flue gas composition responses. The flue gas O_2 in oxy mode behaved in a similar way to air combustion and no large changes in the CO_2 and H_2O were seen as a result of load steps and ramps. The results indicated that the crucial control parameter of the flue gas composition dynamics is the RFG/pure O_2 ratio rather than simply the O_2 input. These findings were also supported by literature. When the goal is to alter the fluidization and the firing power in the same way to reach different load levels, the oxidant composition and thus the RFG/pure O_2 ratio should remain similar on all operational levels. As a result, the dynamics of the flue gas recirculation should not disturb the process in these cases.

4.3. *Separate control of oxidant components*

In oxyfuel boilers, the oxygen supply is independent from the RFG flow, meaning that both the pure O_2 from the ASU and the RFG from the process can be adjusted with their own control structures. This gives an additional degree of freedom to the oxy-CFB control design compared to air-firing, which uses a single oxidant component with an unaltered gas composition. As a result, it is possible to use oxidant O_2 contents differing from air and to alter the oxidant O_2 percentage during the operation in oxy mode. In a way, the oxygen supply, temperature and fluidization become decoupled to some degree: the pure O_2 flow is connected to the combustion, while the RFG is mainly responsible for adjusting temperatures

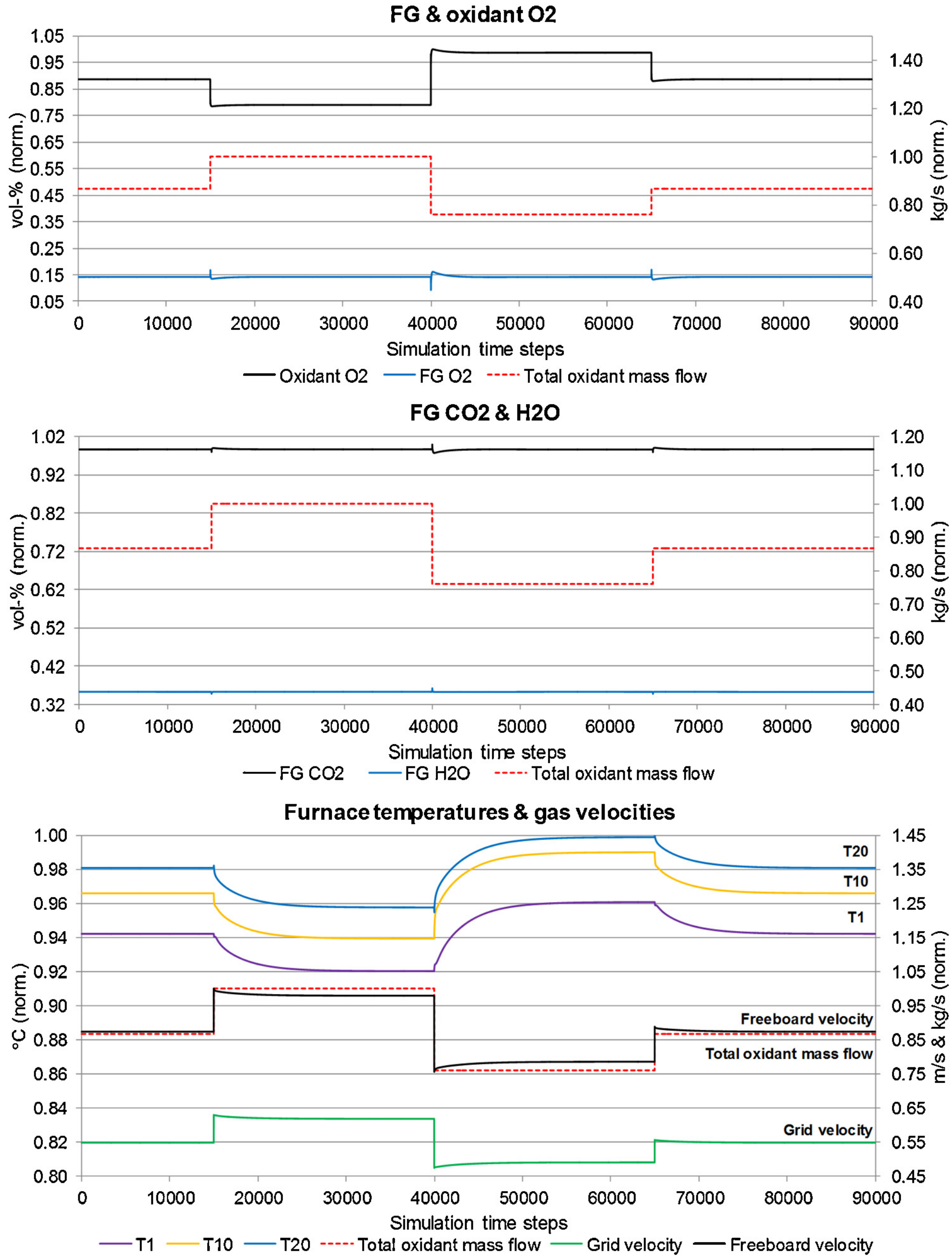

Fig. 8. Normalized simulated flue gas O_2, CO_2 and H_2O responses, furnace temperatures and bed/freeboard velocities for RFG step changes in oxy combustion with a constant firing power (constant fuel and pure O_2 flows).

and fluidization. For example, zone-wise fluidizing RFG flows could be used during load changes to speed up furnace temperature dynamics and to obtain a more uniform temperature profile without directly affecting the combustion. These kinds of considerations introduce entirely new control tasks for solid fuel combustion.

In oxy combustion, the freedom to control the pure O_2 separately from the RFG can be used in flue gas O_2 or oxidant O_2 control. In flue gas O_2 feedback control, one or several pure O_2 or oxidant flows are adjusted according to the measured flue gas O_2 percentage. A flue gas O_2 trim is often compulsory for combustion processes. Like air combustion, the most reasonable flow to be used for flue gas O_2 control is most likely the secondary pure O_2 or oxidant flow, so as not to disrupt the fluidization or the combustion. These control ideas have been illustrated on a conceptual level in Fig. 10, which shows the flue gas O_2 control concepts separately from other hotloop control loops.

Since the pure O_2 can be controlled independently from the RFG, flue gas O_2 control alone will result in a time-variant input oxidant O_2 percentage in oxy combustion, which might be undesirable for the process operation. Oxidant O_2 control concepts (Fig. 11) can be used in oxy combustion to maintain the input oxidant O_2 percentage. The oxidant O_2 is often regarded as a significant process parameter, as it is connected to the pure O_2/RFG ratio and thus the relation between furnace cooling and heat generation. Moreover, the input oxidant O_2 concentration contains information about the flue gas O_2 content because of flue gas recirculation. Oxidant O_2 control is especially important from a safety point of view, as handling gaseous flows with high oxygen contents together with small fuel particles or oxidant preheating might pose risks for the solid fuel power plant. Oxidant O_2 control is essentially a feedforward control solution, as its aim is to supply an oxidant stream with a certain O_2 percentage, regardless of its effect on the combustion.

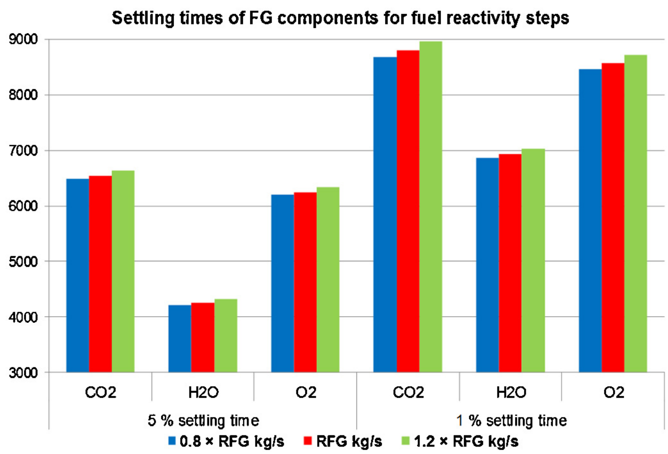

Fig. 9. ±1% and ±5% settling times (time steps) of flue gas CO_2, H_2O and O_2 contents with different flue gas recirculation rates, when the fuel mass flow was decreased with a 10% step. "RFG kg/s" is the nominal RFG mass flow value for the respective load level.

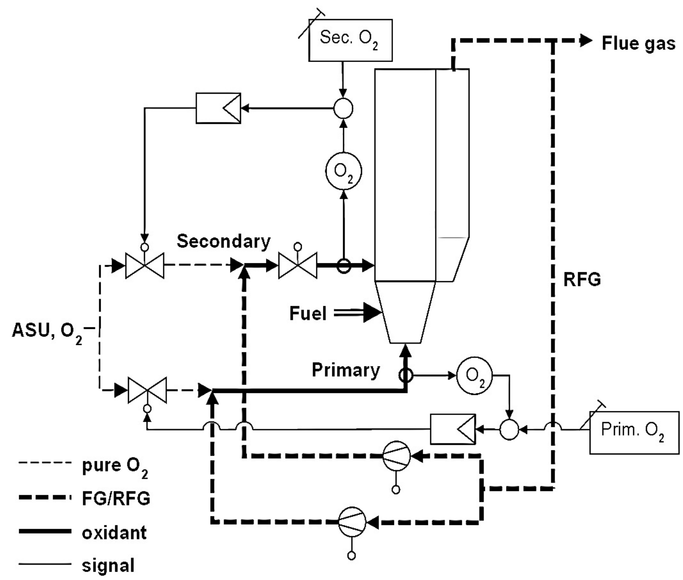

Fig. 11. Example of an oxidant O_2 control concept in oxy-CFB. The primary and secondary pure O_2 flows are used to control the respective O_2 contents. The control is shown on a conceptual level and the figure only displays the oxidant O_2 control, excluding other hotloop control loops.

The oxidant O_2 content can be maintained by adjusting either the pure O_2 flow or the RFG flow. As stated in Section 3 (also illustrated in Fig. 11), the oxidant O_2 percentage should preferably be adjusted with the pure O_2 flows and by modifying the fuel input accordingly. However, controlling the oxidant O_2 without considering the changes in the fluidization might not be enough for the CFB operation. As a result, it might be necessary to control the input gas flow rate beside its O_2 content in oxidant O_2 control. A combined flue gas O_2, oxidant O_2 and total oxidant flow control structure (Fig. 12) would offer a convenient way to control the oxygen input, the combustion and the fluidization in the boiler, even though attention must be paid to conflicting control actions in this solution. Oxidant O_2 control could also be applied only to certain input gas flows.

In oxy combustion, the oxygen excess is easier to maintain at a desired level than in air combustion, as the pure O_2 flow can be determined based on the fuel requirement of the load level, while the RFG flow can be set according to the desired CFB gas velocity. It is also important to note that the excess air supply of air-firing differs from the excess in oxy-firing, as the λ parameter has to be selected in a different way for a pure O_2 flow with no N_2 and as flue gas recirculation reduces the flue gas flow in the boiler. O_2 excess considerations are important in oxy combustion, because too high λ values carry an ASU oxygen production energy penalty.

One particular advantage and challenge for oxyfuel control is presented by the possibility of using different oxygen concentrations for different oxidant inlets (primary air, secondary air, etc.). This is called oxidant O_2 staging and it can be used in oxy combustion to provide improved furnace profile control for e.g.

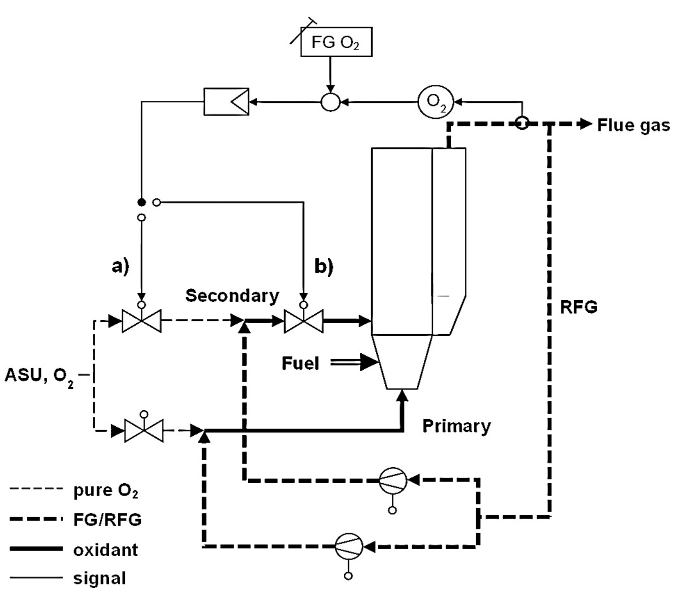

Fig. 10. Flue gas O_2 control concepts in oxy-CFB. The secondary pure O_2 (a) and the secondary oxidant (b) are used to control the flue gas O_2 content. The control is displayed on a conceptual level and the figure only shows the flue gas O_2 control, excluding other hotloop control loops.

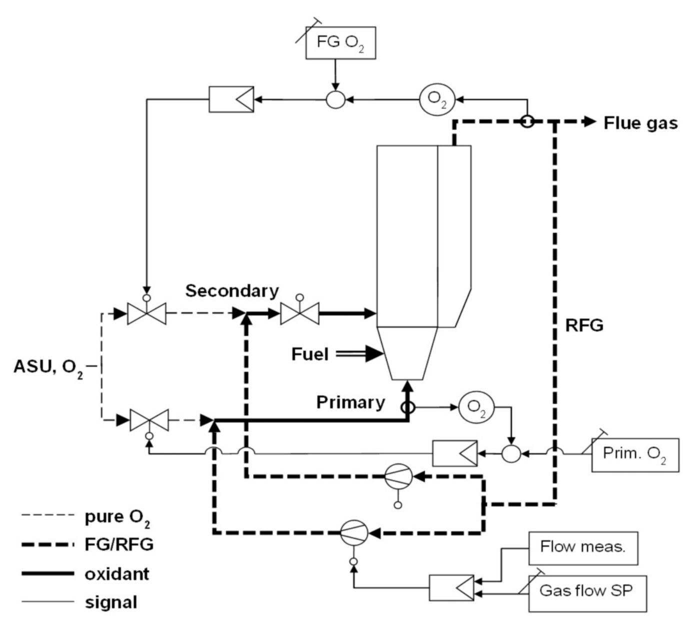

Fig. 12. Concept for input oxidant control: combined flue gas O_2, primary oxidant O_2 and total input oxidant flow control. The gas volume/mass flow measurement can be designed in various ways. The control is illustrated on a conceptual level and the actual implementation is not considered here.

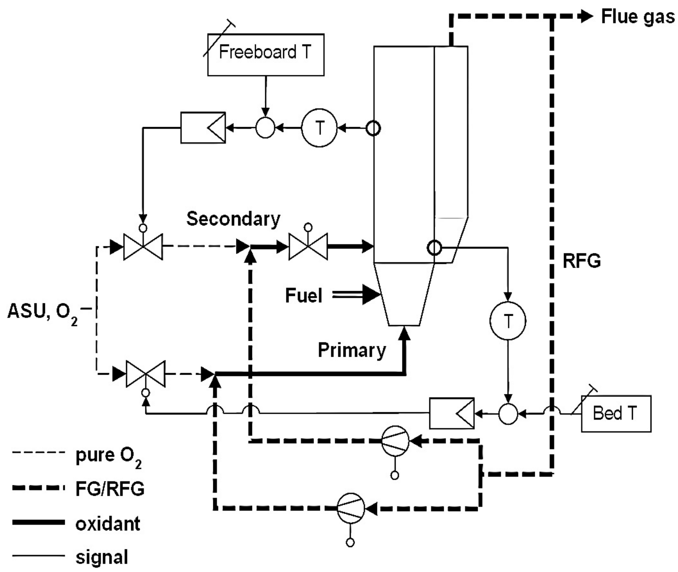

Fig. 13. Oxidant O_2 staging concept for adjusting riser temperature profiles. The primary oxidant O_2 content is used to modify the dense bed temperature, while the secondary oxidant O_2 content controls the freeboard temperature. The solution is shown on a conceptual level: no other control loops are included and the implementation of control loops or measurements is not considered.

temperatures and heat transfer (Fig. 13). Through oxygen staging, the main combustion zone can be shifted along the bed, which affects the principal burning zones of volatiles and char, as well as the oxidative and reductive potentials of the bed. When a low oxidant O_2 level is used in the dense bed, char ascends higher up in the riser, leading to a more uniform riser temperature profile, but possibly also to increases in unburned fuel, the flue gas O_2 content and exhaust gas heat losses. An elevated O_2 content of the primary oxidant, on the other hand, prolongs the contact between the fuel and the oxygen, improving the combustion efficiency, but also increasing the temperature differences along the furnace (Duan et al., 2011). If oxygen staging is used in the hotloop control, it has to be taken into account in the boiler O_2 control designs and it should not clash with systems such as flue gas O_2 control.

Oxidant O_2 staging could be used to selectively assist load transitions in certain parts of the riser. This might be important for load changes with slow and large responses in the furnace temperatures and the heat transfer, as was hinted by the oxy-ramp hotloop model validation simulations. Interestingly, oxygen can also be fed directly into the oxy-firing furnace bed to perform more extreme operations related to combustion and temperature control (McDonald & Zadiraka, 2007). This oxygen boost might help to increase the speed of transitions between combustion modes or load levels and provide a significant advantage in oxy combustion compared to air-firing.

The oxyfuel oxidant temperature presents additional variation to the furnace temperatures compared to air-firing, as the oxidant is a mixture of low-temperature oxygen and RFG from the process flue gas line, much unlike an air flow. If extensive air flow preheating or RFG cooling is not used to make the gas temperatures similar in both combustion modes, oxidant temperature differences will almost certainly occur. Preheating is often not an option in oxy mode due to safety aspects of handling pure oxygen flows or oxidants with elevated O_2 percentages. The oxidant temperature issue might be especially problematic during air-oxy-air switches, as the RFG is a reaction product of the process, leading to potential oxidant temperature changes during the switch. The oxidant temperatures will further be reflected in the furnace temperatures.

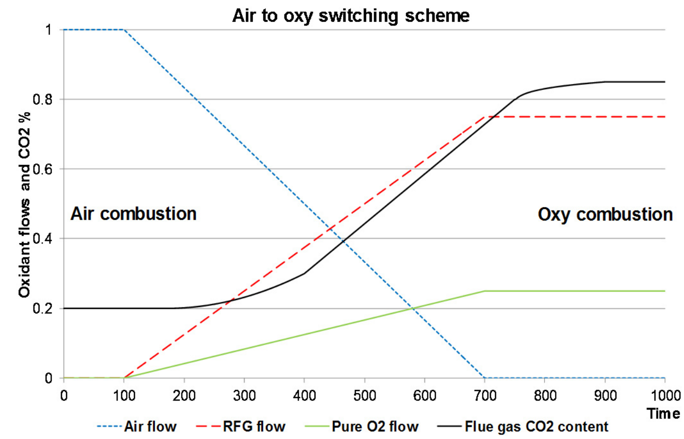

Fig. 14. Air to oxy switch schematic with matching ramp speeds and starting times for all inputs.

It is evident that the number of control possibilities for the oxy-CFB plant will increase compared to air-firing. The flue gas O_2, oxidant O_2 and total gas flow controls can be combined in various ways and the oxyfuel oxidant components can be used to adjust different furnace properties. This will complicate the overall control structure of the power plant and make control design more challenging. In a sense, the SISO control problem of air-firing becomes more of a MISO problem in oxy mode. One approach to facilitate the design could be to put more emphasis on controlling input oxygen mass flows instead of the total oxidant flows and their O_2 percentages, as the oxidant O_2 percentage alone offers no definite information about the actual oxygen input to the process. This was pointed out by Fig. 8, as the flue gas O_2 base level remained constant throughout the testing despite the significant changes in the oxidant O_2 percentage. The oxygen mass flow control concept would potentially lead to a more straightforward control solution.

4.4. Switch dynamics

One specific point of concern in the control of the oxyfuel oxidant components lies in the air-oxy-air switches and in the transitions between oxy modes with different oxidant O_2 contents. These tasks are especially challenging, as up to three different gaseous inputs (oxygen, RFG and air) and the solid process flows

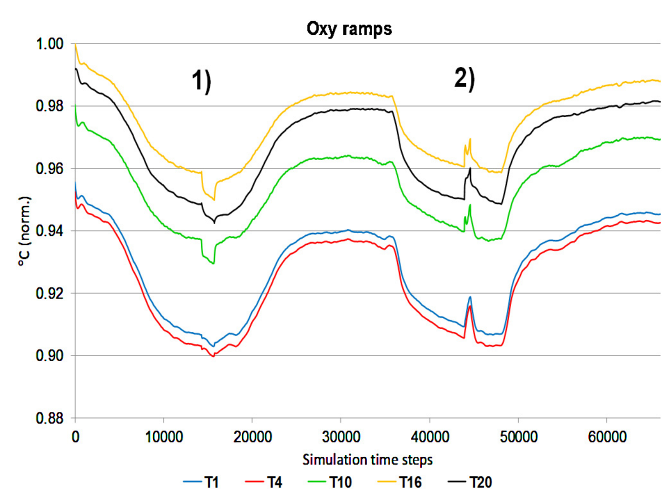

Fig. 15. Normalized furnace temperature responses at different riser heights (T) for two oxy load ramp sets (ramp to a lower load level and back, similar load change), hotloop model validation simulations. The input flow ramping speeds of set (2) were three times larger than those of set (1).

(at least one fuel flow and limestone) need to be adjusted simultaneously. Furthermore, the sequence of the input adjustments has to be determined, which is more complicated in oxy-firing than with an air input flow. The relation between the solid and gaseous inputs is especially important. As a result, input flows need to be coordinated in order to keep process variables at their desired values and achieve stable combustion mode transitions.

Switching between air and oxy mode requires great care, as fast switches have a tendency to cause rapid changes in furnace temperatures and FB velocities (Romeo et al., 2011), which may disturb the process operation. At the same time, switches should also be performed with a required speed, especially when they are based on load demands or cost factors. Fast transitions between combustion modes are also attractive, as the major changes in the flue gas composition take place at the end of the switch ramping (see Section 4.2). The control problem is further complicated by the possible interactions between the switching schemes and the control loops of the process. This might produce unexpected responses and limitations to the switch, which might require decoupling or feedforward control actions.

Testing different switching methods is an integral part in the characterization of oxy-CFB process dynamics. Switches between air and oxy mode can be conducted in different ways by varying the slopes and starting times of gaseous and solid input transition ramps between combustion mode steady-states. The switching scheme often contains one main gaseous flow ramp, during which the major changes in the air, pure O_2 and RFG take place. Ramping sequences with similar ramping speeds for all gaseous flows seem to be common in the literature (Fig. 14). In these sequences, the fuel/oxidant O_2 ratio remains constant throughout the switch.

Beside combustion mode switches, the sequencing of process inputs needs to be configured for oxy load changes, as well. For example, it was discovered during oxy load ramp simulations that a fast ramping of process inputs did not necessarily produce a faster temperature response compared to slower ramps. Fig. 15 shows that even though the temperature time constant for the faster ramp set (2) was smaller than for the slower ramp set (1), the response settling time was actually longer for the faster ramps than for the slower ones. It was suspected that the low reactivity of anthracite-based fuels and the simultaneous change of fuel, RFG and O_2 flows made the furnace cooling change faster than the combustion heat generation during the ramps, creating a momentary imbalance between these two factors. This would have the potential to slow down the response, and the effect would be more visible for fast ramps with rapid RFG transitions than for slower ones.

5. Simulations of switches between air and oxy combustion

Air-oxy-air switches present challenges for CFB process control due to their influences on the combustion dynamics. The switches should ensure good fluidization, combustion and heat transfer conditions, and be sufficiently fast for flexible dual-firing operation. In this section, switching schemes between air and oxy combustion are examined with the dynamic 1-D hotloop model.

5.1. Test setup

The simulated switching schemes from air-firing to oxy-firing were derived from pilot tests. In all simulations, the starting state was air combustion and the target state full oxy mode with oxidant O_2 enrichment. The pure O_2 input was mainly used for oxidant O_2 enrichment and the elevated pure O_2 flow was accompanied by an increase in fuel power. Different oxidant O_2 percentages above 21 vol.% (typically 28 vol.%) were examined in oxy mode to obtain air-like combustion temperatures. In the tested switches, the normal volumetric flow rate (in STP conditions) of the total input gas flow was kept constant. Apart from the final oxy-firing states, a switching scheme could include possible intermediate states for the fuel flow and the oxidant O_2 content.

In the switching schemes reported here, a "direct" ramp was compared to a "sequenced" approach to investigate the relation between gaseous (pure O_2, RFG, air) and solid inputs (fuel and limestone). In the "direct" method (Fig. 16), the solid feeds were ramped together with the pure O_2, RFG and air flows. All ramps were started and ended at the same time, making the method fast. In the "sequenced" method (Fig. 17), the RFG, pure O_2 and air flows were first ramped from air (21 vol.% O_2) to oxy mode without oxidant O_2 enrichment. After the main gas flow ramps, the oxidant O_2 content and the solid feeds were raised to their full oxy mode setting.

The minor anomalies in the sequences of Figs. 16 and 17 were due to the pilot testing practical implementation and they were also reflected in the simulation test runs. Similarly, the fuel power level increase in the "sequenced" method was simulated with a few small steps in the fuel mass flow. Note that analysis of the pilot test outcomes is outside the scope of this paper.

5.2. Simulation results

The two switching schemes resulted in significantly different process responses. The "sequenced" scheme was more affected by

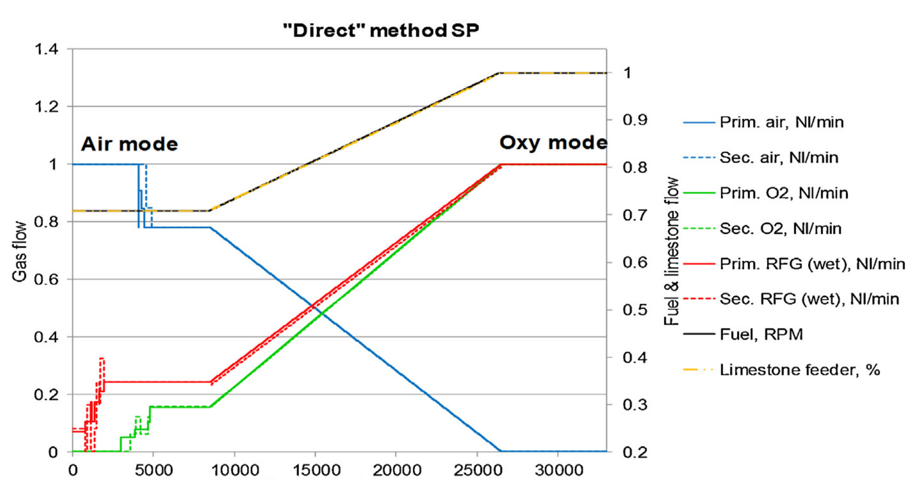

Fig. 16. Input flow setpoints of the "direct" air to oxy switch method. The fuel flow was increased simultaneously with the main gas flow ramps. The normalized inputs correspond to percentages.

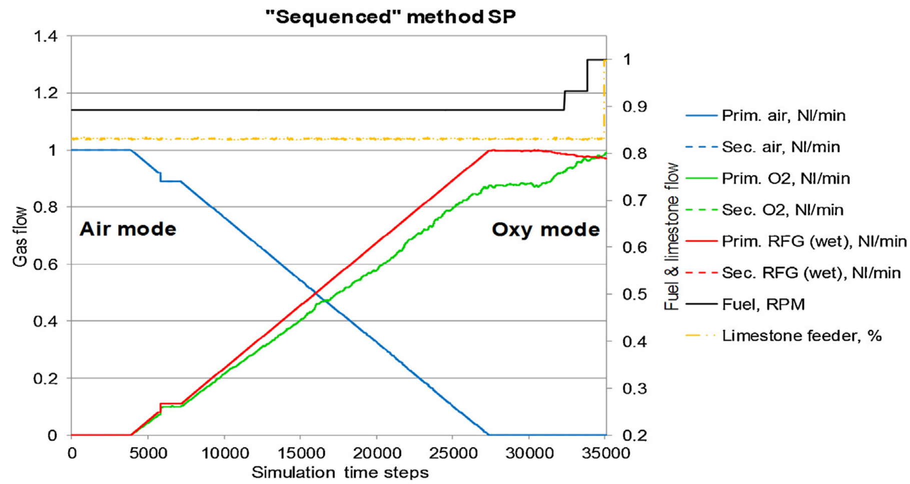

Fig. 17. Input flow setpoints of the "sequenced" air to oxy switch method. The fuel was increased gradually after the main gas flow ramping. The normalized inputs correspond to percentages.

the oxyfuel gaseous medium specific heat capacity elevation than the "direct" method (Fig. 18). As the CO_2 and H_2O concentrations in the oxidant increased, the furnace temperatures slowly decreased for the "sequenced" switch. The lowest temperatures were observed during the final stages of the main gas flow ramps before the oxidant O_2 content elevation and the temperatures regained their original levels, when the fuel steps were performed. This illustrated the phenomena discussed in Sections 3 and 4. In the "direct" scheme, the change in the fuel firing rate was conducted simultaneously with the shift in the atmospheric conditions. Therefore, the temperature drop associated with the heat capacity increase was compensated. The transition in the furnace temperatures from

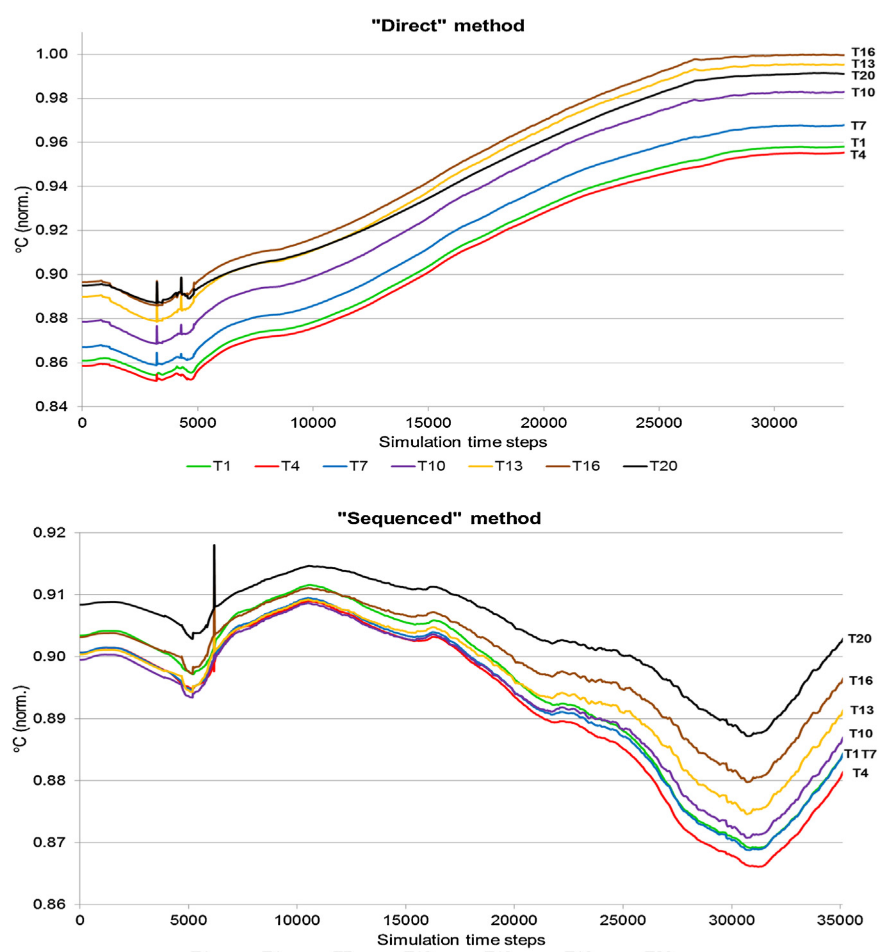

Fig. 18. Simulated furnace temperatures of different riser calculation elements (T) for the "direct" and "sequenced" switch simulations, normalized by the global furnace temperature maximum.

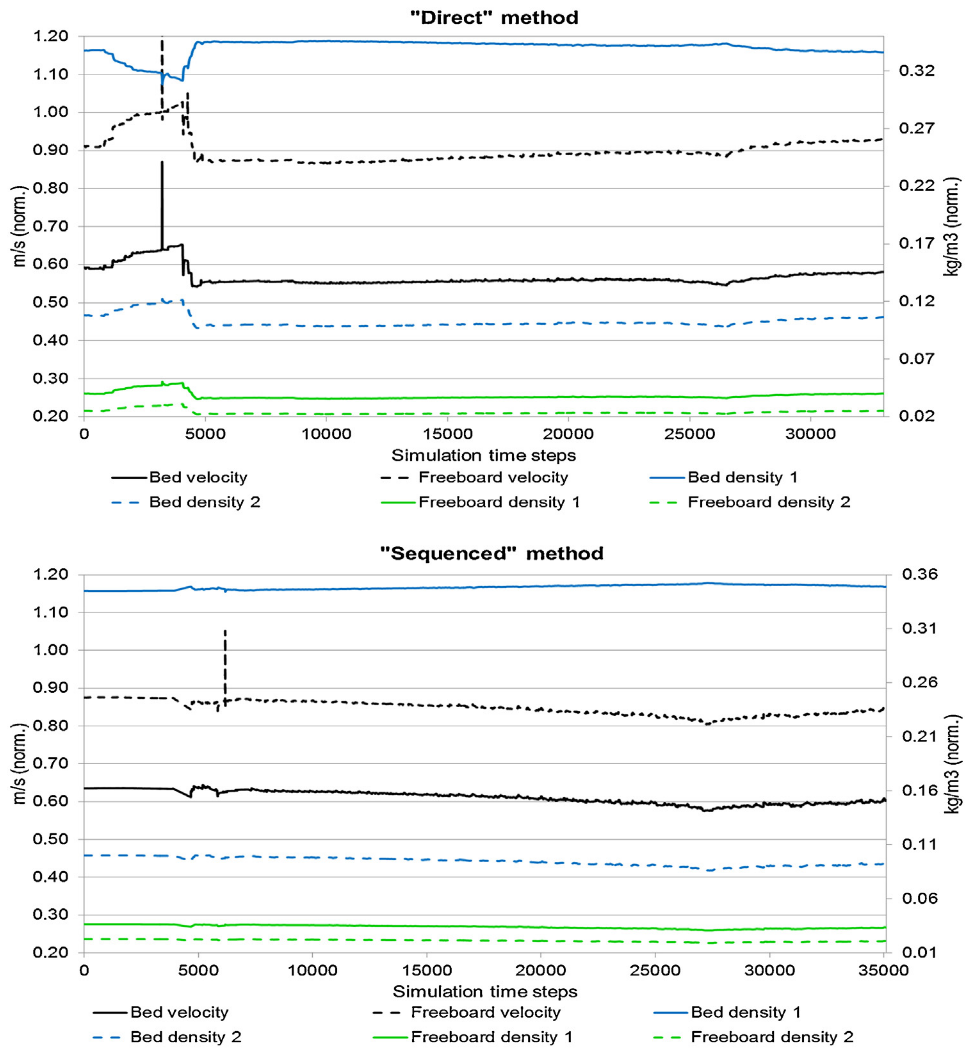

Fig. 19. Simulated bed/freeboard velocities and solids densities of different riser elements (points 1 and 2, point 1 located lower than point 2) for the "direct" and "sequenced" switch simulations, normalized by velocity and global density maxima in the furnace.

air to full oxy mode was smooth and the full oxy-firing steady-state temperatures were reached faster than in the "sequenced" method.

In both switching schemes, the deviations between different temperatures in the CFB riser increased in oxy combustion compared to air combustion. This was most likely caused by the different input oxidant temperatures in air- and oxy-firing. In oxy combustion, the primary and secondary oxidants had the same temperatures, while primary air preheating was used in air mode. The lower secondary air temperature thus led to a more even temperature profile in air mode than in oxy mode. E.g. oxidant O_2 staging could be used as a solution for this issue in oxy mode.

The simulations indicated that it was possible to achieve oxy mode combustion temperatures comparable to those of air mode, if oxidant O_2 enrichment was used. With the selected fuel type, the oxidant O_2 concentrations of the "sequenced" method were close to the ones required by air-like furnace temperatures. The final temperatures of the "direct" scheme were higher than this due to its slightly higher oxidant O_2 enrichment level. The heat transfer power values for the various riser elements followed the trends in the furnace temperatures.

Fluidization during switches was analyzed by examining the gas velocities in the bed and the freeboard, as well as the respective solid material densities (Fig. 19). In general, the gas velocities remained relatively constant throughout the switches, ensuring proper fluidization conditions. The solids densities were in close agreement with the velocities: whenever the gas velocity increased, the dense bed solids content decreased and the densities higher up in the riser increased.

On closer inspection, the "direct" method seemed to produce better fluidization conditions than the "sequenced" switch. The small density and velocity variations during the switch were also less monotonous in the "direct" method than for the "sequenced" switch. The "sequenced" scheme showed a reduction in fluidization at the end of the main gas flow ramps, although the input gas normal volumetric flow rate remained constant. The changes in the fluidization could be addressed to the observed drop in furnace temperatures before the oxidant O_2 enrichment, as the actual input gas volume flow entering the process was altered due to thermal expansion. This highlights the importance of keeping furnace temperature levels constant during the switch. The changes in the fluidization were mostly dictated by the furnace temperatures rather than the oxidant temperatures.

A flue gas and oxidant density increase in oxy mode was clearly observed for both switching methods (Fig. 20). The differences between the methods were quite small, as the main density changes took place during the main gas flow ramps and the densities

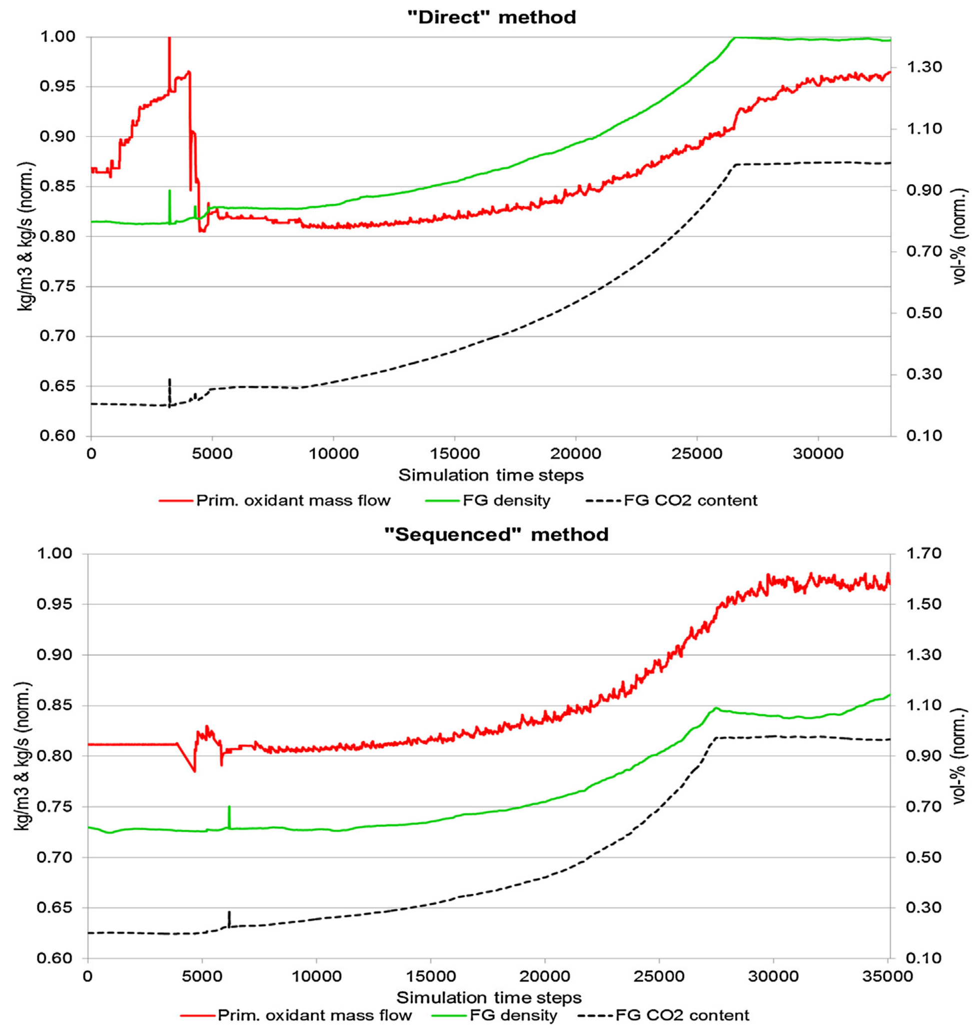

Fig. 20. Flue gas densities (calculated with the ideal gas law and water-steam tables), input primary oxidant mass flows and flue gas CO_2 contents for the "direct" and "sequenced" switch simulations, normalized by the respective maxima.

showed a non-linear response to the switches. The results also displayed that maintaining a constant oxidant volumetric flow caused an increase in the gas mass flow. However, any effects the density changes had on the fluidization were not directly visible in Fig. 19. The flue gas CO_2 and H_2O responses were very similar for the two methods and the component concentrations especially increased towards the end of the gas flow ramping. The flue gas SO_2 marked no preference between the switching methods.

The flue gas O_2 contents (Fig. 21) remained largely constant during both switches and the differences between the methods were small. Since the combustion of fuel was not radically affected by the shift in the atmosphere, air-like combustion conditions could be obtained in oxy mode. The small variability in the flue gas O_2 was particularly surprising for the "direct" scheme, which included rapid and large changes in the process inputs. Some flue gas O_2 drops could be observed during the oxidant adjustments prior to the main gas flow ramps, when air was replaced by RFG with a significantly lower O_2 content. This illustrated the fact that air, pure O_2 and RFG need to be considered as a combined gaseous input during the switch rather than as individual flows.

On a whole, the switch simulations indicated that feasible transitions between air and oxy mode can be performed in CFB boilers. The main differences between the methods were observed in the furnace temperatures, as the fluidization properties were linked to the temperatures. The flue gas O_2 content behaved similarly for both switching schemes and indicated similar oxy-firing combustion conditions to air-firing. The other flue gas emission responses were very similar for both schemes.

The "sequenced" method resulted in a rather slow combustion mode switch with an intermediate drop in furnace temperatures, which was connected to the elevation in the gas specific heat capacity. The "direct" method resulted in smoother and faster temperature responses than those of the "sequenced" method and the drop in furnace temperatures could be compensated with the firing power. "Direct" switching can turn out to be especially useful for rapid transitions, when requirements for combustion and heat transfer are high (e.g. cost/demand-based switches). However, the extensive adjustments to the manipulated variables of the "direct" method might be restrictive in real-world applications. This was already hinted during pilot experiments, with partial clogging of the boiler grid and setpoint tracking problems for the RFG. The simultaneous ramping of all inputs may be more sensitive to process disturbances and more challenging to conduct than a gradual switch. The "sequenced" method thus has potential for startups and shutdowns, when the speed requirements are less strict and when simultaneous input changes are not necessarily feasible. In the separate fuel and gas flow ramping, particular attention has to be paid on the last stages of the oxidant ramps because of the changes in the gas specific heat capacity and the furnace temperatures.

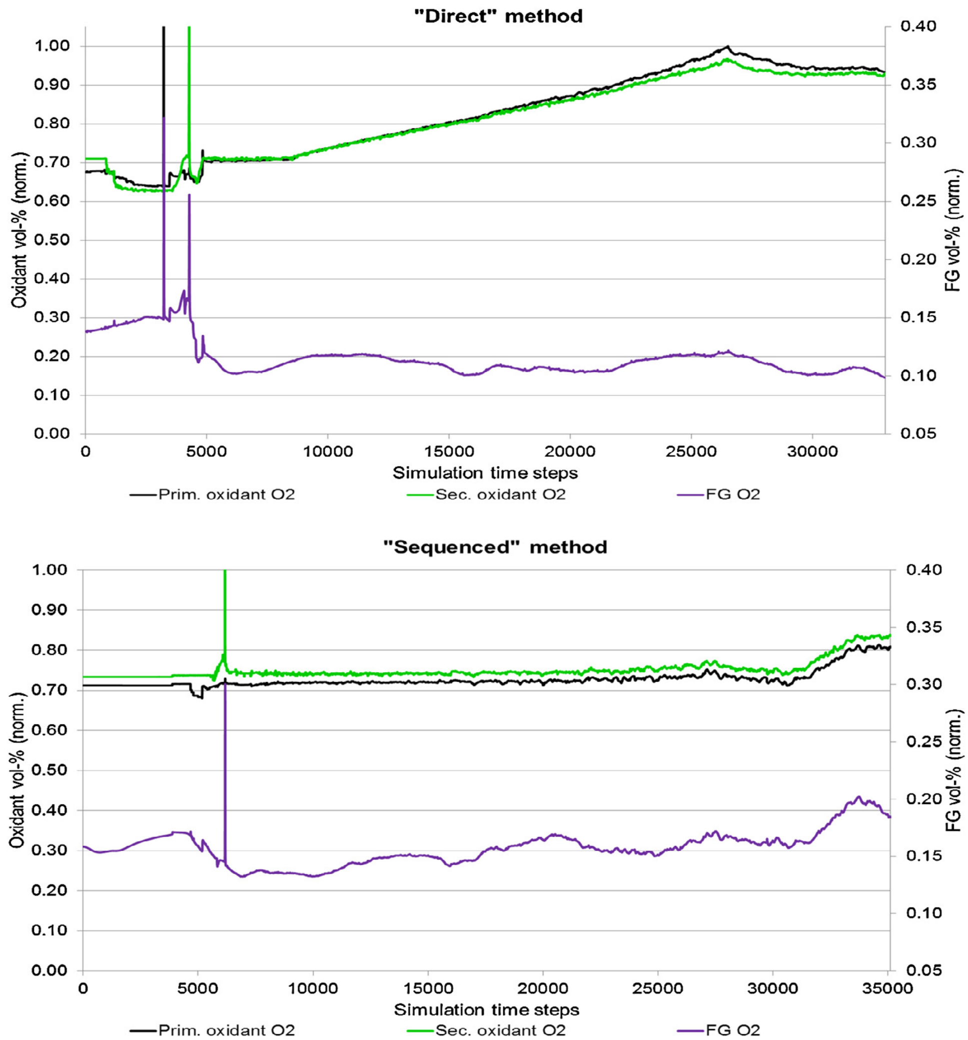

Fig. 21. Flue gas and oxidant O_2 concentrations for the "direct" and "sequenced" switch simulations, normalized by the oxidant O_2 percentage maximum.

6. Conclusions

This paper investigated the differences between oxy- and air-firing in circulating fluidized bed (CFB) boilers. Specific oxy-firing CFB combustion control features and process dynamics were highlighted. Both static and dynamic aspects of the process were investigated through physical considerations and dynamic hotloop simulations. In particular, oxy-CFB control structures were discussed. Two switching methods between air- and oxy-firing were examined through simulations, with the focus on determining how combustion mode transitions should be carried out in the CFB.

The oxidant and flue gas specific heat capacities and densities will be elevated in the oxyfuel boiler compared to air-firing due to the higher gas CO_2 and H_2O contents. The increase in the heat capacity leads to lowered furnace temperatures, slower temperature responses and possible shifts in heat exchanger duties. The temperature level changes can be compensated by increasing the pure O_2 and fuel inputs in oxy mode, i.e. through oxidant O_2 enrichment. To maintain a similar fluidization in air and oxy mode, the input gas volume flow should be kept constant during combustion mode transitions. The oxyfuel atmosphere also influences the combustion and emission formation, e.g. by reducing the diffusivity of oxygen and small hydrocarbons and by increasing fuel gasification.

Flue gas recirculation introduces specific process dynamics to oxyfuel boilers, as the RFG is both a reaction product and the main component of the oxidant flow. The recirculation will add to the time delay of the system and introduce an internal feedback to the process. Although steady-state concentration levels are not affected by the flue gas recirculation amount, the RFG flow determines the concentration dynamics. This is particularly important for air-oxy-air switches, and the RFG/pure O_2 ratio is also an important control parameter for load changes in oxy combustion.

The possibility to adjust the RFG and pure O_2 inputs separately from each other introduces an additional degree of freedom for oxy-CFB control. The RFG is mainly responsible for fluidization and furnace cooling, while the pure O_2 input is regulated by the fuel firing power. Separate pure O_2 and RFG flows enable a more accurate and zone-wise control of furnace properties, profiles and dynamics, including the possibilities to use varying oxidant O_2 percentages, different oxidant O_2 contents for different inlets (O_2 staging), as well as oxygen boosts or extra RFG flows during load or combustion mode transitions. On the other hand, the separate oxidant components call for more advanced combustion control solutions, increasing the complexity of the overall power plant control structure. One comprehensive way to design the combustion control in the oxy-CFB would be to combine a flue gas O_2 trim with oxidant O_2 control and total oxidant volume flow control.

For air-oxy-air combustion mode switches, the most important thing to consider is how the fuel, limestone, pure O_2, RFG and air flows should be altered to obtain optimal combustion, fluidization and heat transfer conditions throughout the switch. Particular attention has to be paid to the relation between solid and gaseous flows. Based on the simulation results, fast "direct" transitions between air- and oxy-firing with simultaneous ramping of all input flows should be used whenever possible. This switching method produced smooth temperature transitions with no decreases in furnace temperatures or deterioration of combustion and fluidization conditions. However, these switches may be challenging to perform correctly. If "direct" switching results in changes that are too extreme for the process, the fuel flow should be altered only after the main gas flow ramping. With this "sequenced" method, a drop in the furnace temperatures due to the elevated oxyfuel oxidant heat capacity should be expected at the end of the main gas flow ramping. This decrease will also be reflected in the fluidizing gas velocities due to temperature effects on the oxidant volume flow.

Air-fired combustion control cannot be applied directly to the oxy-CFB, as the specific features and dynamics of oxy combustion need to be considered in the control design and tuning. Indeed, oxy combustion presents both challenges and advantages for boiler control. Future oxy-CFB control research will involve implementing control solutions for the process and investigating new control possibilities e.g. by ramping oxidant components in different ways during load and combustion mode transitions. Oxy-CFB control should also be analyzed on a plant-wide scale, as the greatest challenges for the technology are derived from the operating costs, efficiency penalties and performance restrictions of oxygen production (ASU) and CO_2 processing units (CCU + CPU). Furthermore, as the oxyfuel gaseous atmosphere influences heat transfer in the boiler, water-steam side modelling should be included in the oxy-firing power plant simulations.

Acknowledgements

The authors would like to acknowledge the cooperation between the University of Oulu and Foster Wheeler Energia Oy (Varkaus, Finland). Funding has been received from the Graduate School in Chemical Engineering (GSCE). The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement no. 239188. For the experimental research related to previous hotloop model validation, acknowledgements go to the VTT Technical Research Centre of Finland (Jyväskylä, Finland). The work of the Lappeenranta University of Technology (LUT) has been important for the hotloop model development.

References

Basu, P. (2006). *Combustion and gasification in fluidized beds*. Boca Raton: CRC Press, Taylor & Francis Group.

Czakiert, T., & Nowak, W. (2010). Kinetics of coal char combustion in oxygen-enriched environment. In G. Yue, H. Zhang, C. Zhao, & Z. Luo (Eds.), *Proceedings of the 20th international conference on fluidized bed combustion; 2009 May 18–21* (pp. 618–623). Xi'an, China/Beijing: Springer/Tsinghua University Press.

Czakiert, T., Sztekler, K., Karski, S., Markiewicz, D., & Nowak, W. (2010). Oxy-fuel circulating fluidized bed combustion in a small pilot-scale test rig. *Fuel Processing Technology*, *91*(November (11)), 1617–1623.

Czakiert, T., Bis, Z., Muskala, W., & Nowak, W. (2006). Fuel conversion from oxy-fuel combustion in a circulating fluidized bed. *Fuel Processing Technology*, *87*(June (6)), 531–538.

Davidson, R. M., & Santos, S. O. (2010, June). *Oxyfuel combustion of pulverized coal*. London (UK): IEA Clean Coal Centre. Report No.: CCC/168, ISBN: 978-92-9029-488-7.

Duan, L., Zhao, C., Zhou, W., Chengrui, Q., & Chen, X. (2011). O_2/CO_2 coal combustion characteristics in a 50 kW_{th} circulating fluidized bed. *International Journal of Greenhouse Gas Control*, *5*(July (4)), 770–776.

Eriksson, T., Sippu, O., Hotta, A., Fan, Z., Myöhänen, K., Hyppänen, T., et al. (2007). Oxyfuel CFB boiler as a route to near zero CO_2 emission coal firing [Internet]. In Power-Gen Europe (Ed.), *15th POWER-GEN Europe conference, conference proceedings – power-gen europe [CD-ROM]*; 2007 June 26–28; Madrid, Spain. Madrid (ES): PennWell Corporation [cited 2011 Nov 28]. Available from http://www.fwc.com/publications/tech_papers/files/TP_CCS_07_02.pdf

Foster Wheeler Energia Oy. Foster Wheeler figure material [database]. Varkaus: Foster Wheeler Energia Oy; [Date unknown] [updated 2012; cited 2013 June 05]. Available from internal company database.

Hack, H., Fan, Z., Seltzer, A., Eriksson, T., Sippu, O., & Hotta, A. (2008). Development of integrated flexi-burn dual oxidant CFB power plant [Internet]. In American Society of Mechanical Engineers: Power Division, United States: Department of Energy, National Energy Technology Laboratory (US), Coal Technology Association, American Public Power Association (Eds.), The Proceedings of the 33rd International Technical Conference on Coal Utilization & Fuel Systems; June 01–05. Clearwater (FL), USA. Clearwater (FL, US): Coal Technology Association 2008 [cited 2011 Nov 28]. Available from http://www.fwc.com/publications/tech_papers/files/TP_CCS_08_02.pdf

Hasegawa, T. (2013). Development of semiclosed cycle gas turbine for oxy-fuel IGCC power generation with CO_2 capture. In E. Benini (Ed.), *Progress in gas turbine performance* (pp. 25–50). Rijeka: InTech.

Ikonen, E., Kovács, J., & Ritvanen, J. (2013). Circulating fluidized bed hot-loop analysis, tuning, and state-estimation using particle filtering. *International Journal of Innovative Computing, Information and Control*, *9*(August (8)), 3357–3376.

IPCC. (2005). 3 capture of CO_2. In B. Metz, O. Davidson, H. C. de Coninck, M. Loos, & L. A. Meyer (Eds.), *Working group III of the intergovernmental panel on climate change. IPCC special report on carbon dioxide capture and storage* (pp. 105–178). Cambridge (UK) and New York (NY, US): Cambridge University Press.

McDonald, D. & Zadiraka, A. (2007). Control of pulverized coal oxy-combustion systems [Internet]. In The International Society of Automation (ISA) (Ed.), *Power – 17th annual ISA power industry division and EPRI controls and instrumentation conference [CD-ROM]* 2007 June 10–15, Pittsburgh (PA), USA. Pittsburgh (PA, US): ISA; [cited 2011 Nov 28]. Available from http://www.babcock.com/library/pdf/BR-1798.pdf

ya Nsakala, N., Liljedahl, G. N., Marion, J., Levasseur, A. A., Turek, D., Chamberland, R., et al. (2004). Oxygen-fired circulating fluidized bed boilers for greenhouse gas emissions control and other applications [Internet]. In The National Energy Technology Laboratory (NETL) (Ed.), *3rd annual conference on carbon capture & sequestration, conference proceedings [Internet]*; 2004 May 03–06; Alexandria (VA), USA. Alexandria (VA, US): NETL, U.S. Department of Energy (DOE) [cited 2011 Nov 28]. Available from http://www.netl.doe.gov/publications/proceedings/04/carbon-seq/031.pdf

Ritvanen, J., Kovács, J., Salo, M., Hultgren, M., Tourunen, A., & Hyppänen, T. (2012). 1-D dynamic simulation study of oxygen fired coal combustion in pilot and large scale CFB boilers. In International Conference on Fluidized Bed Combustion (Ed.), *21st international conference on fluidized bed combustion proceedings* (Vol. 1, pp. 72–79). 2012 June 03–06; Naples, Italy. Naples (IT): EnzoAlbanoEditore.

Romeo, L. M., Díez, L. I., Guedea, I., Bolea, I., Lupiáñez, C., González, A., et al. (2011). Design and operation assessment of an oxyfuel fluidized bed combustor. *Experimental Thermal and Fluid Science*, *35*(April (3)), 477–484.

Suraniti, S. L., ya Nsakala, N., & Darling, S. L. (2009). Alstom oxyfuel CFB boilers: A promising option for CO_2 capture. *Energy Procedia*, *1*(February (1)), 543–548.

Thorbergsson, E. M. (2012). *Conceptual gas turbine modelling for oxy-fuel power cycles*. Gothenburg (SE): Chalmers University of Technology (Dissertation)

Toftegaard, M. B., Brix, J., Jensen, P. A., Glarborg, P., & Jensen, A. D. (2010). Oxy-fuel combustion of solid fuels. *Progress in Energy and Combustion Science*, *36*(October (5)), 581–625.

Tourunen, A. (2010). *A study of combustion phenomena in circulating fluidized beds by developing and applying experimental and modelling methods for laboratory-scale reactors, Acta Universitatis Lappeenrantaensis 419*. Lappeenranta: Lappeenranta University of Technology (Dissertation).

Wall, T., Liu, Y., Spero, C., Elliott, L., Khare, S., Rathnam, R., et al. (2009). An overview on oxyfuel coal combustion – State of the art research and technology development. *Chemical Engineering Research and Design*, *87*(August (8)), 1003–1016.

Weigl, S. (2009). Modellierung und experimentelle Untersuchungen zum Oxyfuel-Prozess an einer 50 kW Staubfeuerungs-Versuchsanlage ['Dissertation, Internet]. Dresden (DE): Technische Universität Dresden 2009 [cited 2011 Nov 28]. German. Available from http://www.qucosa.de/fileadmin/data/qucosa/documents/2612/100110%20Promotion%20Sebastian%20Weigl.pdf

Yin, C., Rosendahl, L. A., & Kaer, S. K. (2011). Chemistry and radiation in oxy-fuel combustion: A computational fluid dynamics modeling study. *Fuel*, *90*(July (7)), 2519–2529.