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Combustion Control in Oxy-fired Circulating Fluidized Bed Combustion

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Abstract

Oxy combustion control was investigated in the circulating fluidized bed boiler. Oxy combustion is a carbon capture and storage (CCS) technology for capturing power plant atmospheric CO_2 emissions. Oxygen and recirculated flue gas (RFG) are used as an oxidant instead of air, resulting in an increase in the flue gas carbon dioxide concentration and an easier separation of the CO_2. The change in the combustion atmosphere and process input flows leads to alterations in the process operation and its dynamic behavior, such as slower temperature dynamics due to an elevated gas heat capacity, and flue gas composition internal feedback dynamics because of flue gas recirculation. The coordination of fuel and oxidant inputs needs to be considered especially during transients between air and oxy mode. The oxy combustion configuration introduces an additional degree of freedom for combustion control due to the separate oxygen and RFG inputs, which enables a more individual adjustment of the oxygen supply, furnace temperatures and fluidization than in air combustion. The most important control issue to be solved is how flue gas O_2 and oxidant O_2 control should be arranged. The possibility to use oxidant O_2 percentages differing from air and different oxygen contents for different oxidant inlets introduces additional possibilities for influencing furnace profiles. The work examined oxy combustion control through process flowsheet considerations, simulations with a dynamic hotloop model and relative gain analysis with the partial relative gain. Different control concepts are investigated and compared, exploiting the possibilities and manners for controlling the composition of the oxidant flow.

Keywords: power plant; oxy combustion; CFB; CCS technology; process control; relative gain array

1. Introduction

In this paper, combustion control is investigated for oxy combustion in the circulating fluidized bed (CFB) boiler. Carbon capture and storage (CCS) is currently seen as a key technology for reducing CO_2 emissions from fossil fuel power plants. Among the main industrial CCS techniques, oxy combustion has been regarded as one of the most viable options, when considering the cost efficiency and small CO_2 release of the process. In oxy combustion, solid fuel is combusted with a mixture of pure oxygen from e.g. an air separation unit (ASU) and recirculated flue gas (RFG) from the process instead of traditional combustion with air as the oxidant gas. This way, a flue gas with a 70-98 vol-% (dry) CO_2 content can be obtained, enabling an easier recovery of the CO_2 component. These changes lead to a significantly different combustion atmosphere compared to air combustion (Table 1).

Table 1. Typical concentrations of gaseous components in the oxidant and the flue gas before water condensing in air and oxy combustion, data from [1].

	Input oxidant gas		Flue gas	
vol-% in gas (wet basis)	**Air combustion**	**Oxy combustion**	**Air combustion**	**Oxy combustion**
O_2	21	21-30	3-4	3-4
N_2	79	0-10	70-75	0-10
CO_2	0	40-50	12-14	60-70
H_2O	small	10-20	10-15	20-25
NO_x, SO_x	no	yes	yes	yes

Oxy combustion is currently in its pilot testing and early commercialization stage. While upcoming oxy boiler generations might utilize oxidant O_2 percentages significantly above that of air (21 vol-%), the current aim is to obtain combustion conditions similar to air-firing. For example, the Flexi-Burn^{TM} CFB technology of Amec Foster Wheeler (FW) (Figure 1) offers the possibility to operate the same boiler effectively in either air or oxy combustion mode [2]. From solid fuel combustion, research has so far mostly concentrated on pulverized coal boilers, including extensive works from authors like Davidson & Santos [1], Toftegaard et al. [3] and Wall et al. [4]. The topic of this paper, the CFB boiler, has previously been investigated for oxy combustion by e.g. Czakiert et al. [5,6], Duan et al. [7], Eriksson et al. [8], Leckner & Gómez-Barea [9], Romeo et al. [10] and Suraniti et al. [11]. However, few papers have dealt with control issues in oxy-CFB combustion. It's important to realize that although the oxy-firing configuration is a process design issue, it also leads to significant changes in combustion control.

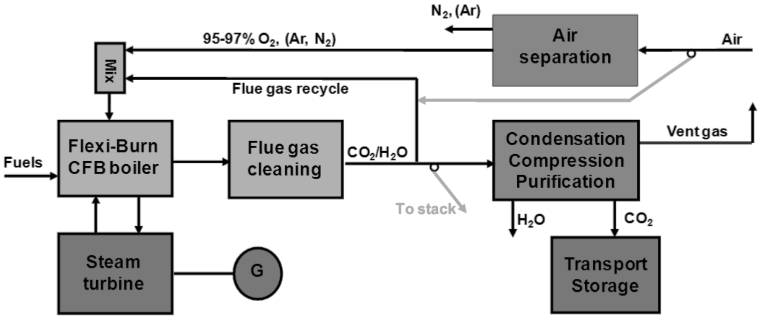

Figure 1. Schematic diagram of a Flexi-Burn^{TM} oxy-CFB power plant [2].

The separation of the oxidant gas flow into individual RFG and pure O_2 components gives an additional degree of freedom for combustion control compared to air-firing. Even though this results in a more complicated selection procedure of the control structure, the configuration gives the possibility to control boiler properties much more accurately than before. The aim of this paper is to look at how combustion control structures should be selected for oxy combustion to ensure the operability of the boiler and take advantage of the increased control possibilities of oxy-firing. Process structural investigations are supported by dynamic model simulations. In addition, plantwide combustion control structures are generated with the partial relative gain analysis method.

2. General oxy-firing effects on CFB combustion

The target process of this work is the circulating fluidized bed (CFB) hotloop, which consists of the fluidized bed furnace, the gas-solid separators, the solids circulation system with its external heat exchangers (e.g. Intrex^{TM} units), as well as the necessary fuel and oxidant gas feeding lines. The water-steam cycle will largely not be considered in this work, as the main differences between oxy combustion and air-fired boilers can be found on the combustion side. When designing CFB combustion control for oxy-firing, the following issues need to be considered [12]:

- **Fluidization:** effect of input gas flows and gas compositions on fluidization conditions
- **Heat transfer:** effect of atmosphere on heat transfer and heat distribution in the boiler
- **Heat generation:** effect of combustion setup on combustion reaction progression and firing power
- **Other reactions:** changes in emission formation and potential unwanted effects like agglomeration
- **Supporting units:** the coordination of the boiler with the ASU and CO_2 processing units

The oxy combustion configuration results in several notable changes for the boiler dynamics [12]. The oxidant and flue gas specific heat capacities and densities are elevated in oxy mode compared to air-firing due to the high CO_2 and H_2O contents of the gas. This leads to lowered furnace temperatures, which can be compensated by increasing the O_2 and fuel inputs (oxidant O_2 enrichment). However, the increase in the gas heat capacity also results in slower temperature responses and possibly even shifts in the heat transfer distribution between heat exchangers. The density change of the oxidant needs to be compensated by keeping the gas volume flow constant during transitions from air to oxy mode. Furthermore, the oxyfuel atmosphere has the potential to influence the combustion and emission formation (e.g. reduced diffusivity of oxygen and hydrocarbons, increased fuel gasification and changes in dominant sulphur capture reaction mechanisms). However, in boiler control problems, emissions are primarily related to other disturbance rejection and setpoint selection issues, especially temperature and O_2 content values. Indeed, most emission components are not regulated through feedback control, or the control system would be the same for air- and oxy-CFB (e.g. SO_X control with the limestone feed).

Flue gas recirculation results in significant internal feedback dynamics in the boiler, as the RFG is the main component of the oxidant. Although steady-state concentration levels aren't essentially affected by the flue gas recirculation amount, an increased RFG amount will lead to larger settling times and time delays. In general, the ability to switch readily between air and oxy combustion provides a great deal of flexibility for the boiler operation, which makes air-oxy-air switches an important part of oxy combustion control investigations. In [12], it was verified through hotloop model simulations that switches between the combustion modes could be conducted in a feasible way. The smoothest transitions were reached, when both the fuel flow and the oxidant gas flows were altered simultaneously.

3. Modeling & methods

3.1 Process model

A dynamic 1-D Matlab/Simulink hotloop model was used for describing the oxy-CFB process in this work. The model has been developed in cooperation between Amec Foster Wheeler (FW), the Lappeenranta University of Technology and the University of Oulu [13]. The model is used as the hotloop component in a family of FW industrial CFB power plant simulators, and the model has been extensively validated for different air-fired boilers and oxy combustion. On its own, the model is used for investigating process dynamics and testing control solutions. In the model, boiler unit components (furnace, separators, Intrex^{TM} heat exchangers) consist of ideally mixed calculation elements (20 elements for the furnace) with mass and energy balance differential equations. A combined energy equation was defined for the gaseous and solid phase element temperatures. The hydrodynamics, combustion characteristics and heat transfer were calculated through empirical and semi-empirical correlations. Surface temperature parameters could be used for simulating water-steam cycle effects. Aside from the main flue gas components, SO_X formation was based on mass balance calculations, and NO_X formation was not considered. As a result, emission control was not investigated separately in this work.

The hotloop model has been validated for oxy combustion with a 20-50/50-100 kW_{th} air-/oxy-fired CFB pilot combustor [2] (Figure 2). The pilot contained a furnace tube, cyclones for solid material separation, a return leg and a proper flue gas recirculation system [14]. The oxidant was formed from RFG from the flue gas line and room temperature bottled O_2 with a purity of 96.6 w-%. Like the validation case, a fuel blend consisting of an approximate 70/30 mass percentage ratio of anthracite and petcoke was used for this work, and the nominal fuel and oxidant mass flows were obtained from the validation simulations.

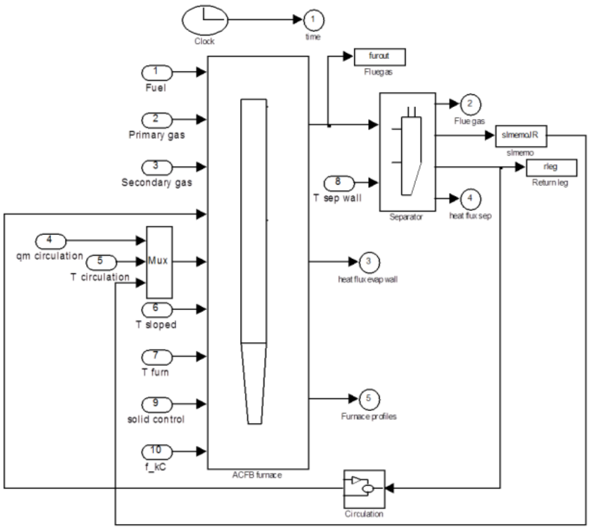

Figure 2. The hotloop module of the air/oxy dynamic model used in this study [12].

3.2 Relative gain analysis and ICI controllability

In this work, plantwide control structures were generated for the hotloop based on the concept of integral controllability with integrity (ICI), using the partial relative gain method (PRG) [15]. In the analysis, a decentralized control system was formed by pairing manipulated inputs and controlled outputs into SISO loops (single input, single output). The PRG is based on the relative gain array (RGA) (1), which is a common method for generating control structures based on system interactions [16]. The RGA forms row/column sums of ones: values close to 1 are good and negative entries are to be avoided. Large elements and elements close to zero may also lead to control problems.

$$\mathrm{RGA}(\mathbf{G}) = \mathbf{G} \times \mathbf{G}^{-\mathrm{T}} = \begin{bmatrix} \lambda_{1,1} & \cdots & \lambda_{1,j} \\ \vdots & \ddots & \vdots \\ \lambda_{i,1} & \cdots & \lambda_{i,j} \end{bmatrix}, \tag{1}$$

where **G** is the system steady-state gain matrix $y = \mathbf{G}u$ (y are outputs, u are inputs) $\lambda_{i,j}$ are relative gains for row i and column j, and "×" is an element-by-element multiplication operator.

Unlike the basic RGA, the PRG (2) considers how relative gain values change, when control loops are closed to form partially controlled systems. The PRG is basically an RGA for a partially controlled subsystem $\mathbf{G}_c$, where the rest of the system is under integral feedback control. The gains of this subsystem can be calculated with (3), when closed loops are under perfect feedback control.

$$\mathrm{PRG}_\mathrm{c}(\mathbf{G}) = \mathrm{RGA}(\overline{\mathbf{G}}_\mathrm{c}) = \overline{\mathbf{G}}_\mathrm{c} \times \overline{\mathbf{G}}_\mathrm{c}{}^{-\mathrm{T}}, \tag{2}$$

$$\overline{\mathbf{G}}_\mathrm{c} = \mathbf{G}_{y_\mathrm{o},u_\mathrm{o}} - \mathbf{G}_{y_\mathrm{o},u_\mathrm{c}} \cdot \mathbf{G}^{-1}_{y_\mathrm{c},u_\mathrm{c}} \cdot \mathbf{G}_{y_\mathrm{c},u_\mathrm{o}}, \tag{3}$$

where PRG_c is the partial relative gain for the set of closed loops c, RGA is the relative gain array, **G** is the steady-state system gain matrix, y_c denotes row indices of controlled outputs, u_c denotes column indices of manipulated inputs, y_o and u_o are indices of remaining open loops, and $\overline{\mathbf{G}}_\mathrm{c}$ is the steady-state partially controlled subsystem matrix with integral feedback control and loops $y_\mathrm{c} - u_\mathrm{c}$ closed.

The PRG can be used for ensuring ICI controllability. A system is ICI, if the controlled system remains stable, when loops are arbitrarily opened and closed or the gains of all loops are detuned by the same factor [15]. ICI is a useful property, as it enables individual control loop tuning without instability. A system **G** (size $n \times n$, manipulated-controlled variable pairings on the diagonal) is ICI, if all diagonal RGA elements and the diagonal PRG elements of all partially controlled subsystems ($k \times k$, $k = 2, 3, \ldots, n-1$) are positive. Condition $k = 2$ is redundant, if the Niederlinski index (4) is positive.

$$\mathrm{NI} = \frac{\det(\mathbf{G})}{\det(\widetilde{\mathbf{G}})}, \tag{4}$$

where **G** is the steady-state system matrix and $\widetilde{\mathbf{G}}$ is the matrix obtained by setting to zero all elements of **G** that do not correspond to an input-output pairing in a given block-decentralized control structure. If the MV-CV pairings are located on the diagonal $g_{i,i}$, the term $\det(\widetilde{\mathbf{G}})$ is simplified to $\prod_i g_{i,i}$.

The hotloop model was used for generating the steady-state gain matrix for the main process inputs and outputs by performing small stepwise changes around the 100 % load level one input at a time, while other inputs remained constant. The basic PRG definition requires square systems, meaning that an equal number of inputs and outputs always had to be selected for RGA/PRG investigations. The PRGs of all partially controlled subsystems were calculated to get control structures with the ICI property for the CFB. The PRG elements of these solutions were assessed with a similar scale to the RGA:

$0 < \lambda < 0.05$	Selection should be avoided, inaccuracies easily lead to negative PRGs.
$0.05 \leq \lambda < 0.1$	Bad selection with poor robustness, risk for singularity or negative PRG.
$0.1 \leq \lambda < 0.5$	Fair, but uncertain selection due to the nonlinear RGA scale.
$0.9 \leq \lambda \leq 1.2$	Extremely good selection, close to ideal interaction value.
$\lambda > 10$	Problematic selection, potentially poor control performance & ill-conditioning.

4. Oxy combustion control design

4.1 Control structure considerations

The pure O_2 and RFG input flows have different effects on the furnace operation. The main purpose of the oxidant is to supply the oxygen needed for combustion. This property translates directly from air-firing to oxy-firing, but at the same time the oxidant is also needed for fluidizing the solids and cooling down the furnace. Since these other properties are mainly connected to the RFG in oxy combustion, the O_2 supply, furnace temperature and fluidization become decoupled to some degree, unlike air-firing with an unaltered oxidant, air. The separate pure O_2 and RFG adjustments make it possible to use oxidant O_2 contents differing from air and to alter the oxidant O_2 percentage during the operation.

The pure O_2 flows can be utilized either for flue gas or oxidant O_2 control in oxy combustion. In flue gas O_2 control, input oxidant flows are adjusted according to the measured flue gas O_2 content. The secondary oxidant is typically used for this purpose, as the primary gas flow is more connected to the load level and the fluidization in the CFB. The basic concepts of oxy flue gas O_2 control can be illustrated with Figure 3, where it needs to be decided, whether structure (a) or (b) should be preferred:

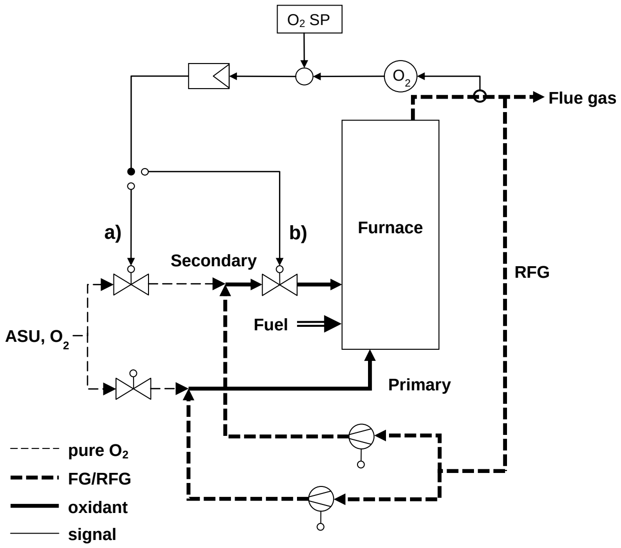

Figure 3. Flue gas O_2 control concepts. The secondary pure O_2 (a) or the total secondary oxidant (b) are used for controlling the flue gas O_2 concentration. SP = setpoint.

- In structure (a), the pure O_2 flow is modified directly, which makes fast compensation of combustion disturbances possible. A change in the pure O_2 flow also results in a smaller change in fluidization than a change in the entire secondary oxidant, as the RFG is the main fluidizing medium. However, structure (a) allows the oxidant O_2 content to vary. Large oxygen input adjustments without similar modifications to the cooling RFG flows can also lead to furnace temperature variations.
- Structure (b) uses a constant oxidant composition, which corresponds to air-firing control. During flue gas O_2 control, the oxygen supply, cooling and fluidization are all altered simultaneously.

Figure 4 shows hotloop simulations for structures (a) and (b) with a -10 % stepwise decrease in the fuel mass flow at 200 time steps. Both solutions were implemented with adequately tuned PID controllers.

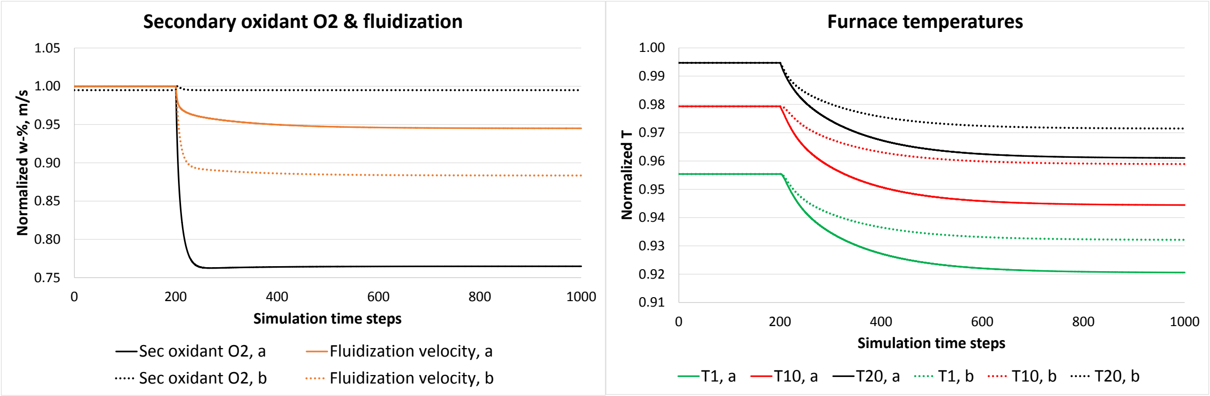

Figure 4. Normalized simulated fluidization velocities, secondary oxidant O_2 contents and element 1/10/20 temperatures for a -10 % fuel step with flue gas O_2 control solutions (a) and (b).

Based on the results, structure (a) was slightly faster for the O_2 control than (b), although both controllers performed well. A significant decrease in the fluidizing gas velocity was observed for control structure (b), while the change was much smaller for structure (a). At the same time, the secondary oxidant O_2 content decreased remarkably in case (a), and there was a larger decrease in the furnace temperatures than for structure (b). However, these conclusions also depend on the nature of the disturbances. For example, flue gas O_2 disturbances that do not cause major changes in the heat generation favor keeping the furnace cooling constant despite O_2 variations, such as in structure (a).

Since individual adjustments to pure O_2 flows result in time-varying oxidant O_2 percentages, oxidant O_2 control might be necessary for oxy combustion (Figure 5). The oxidant O_2 is an indicator of the relation between cooling and heat generation, and it is an important safety constraint for handling solid fuel particles. For these reasons, oxidant O_2 control is beneficial especially for the primary oxidant. The primary oxidant O_2 percentage is most naturally controlled with the pure O_2 flow, as the primary RFG is the main gas flow for fluidization. Implementing oxidant O_2 control to the secondary oxidant is less straightforward, as the same gas flows also need to be used for flue gas O_2 control.

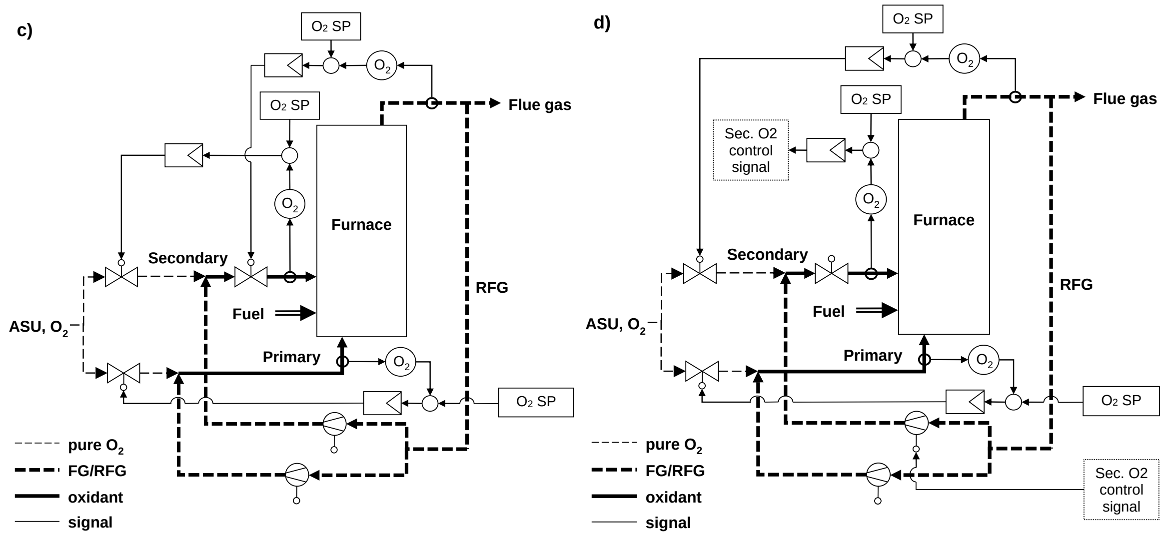

Figure 5. Oxidant O_2 & flue gas O_2 control concepts. The primary pure O_2 is used for primary gas O_2 content control. The secondary pure O_2 (c) or RFG (d) is used for the secondary oxidant O_2, and the flue gas O_2 is controlled with the secondary oxidant (c) or pure O_2 (d). SP = setpoint.

If the total secondary oxidant flow is used for flue gas O_2 control, the pure oxygen is readily available for controlling the oxidant O_2, i.e. structure (c). If the pure O_2 already controls the flue gas O_2, the RFG could be utilized for adjusting the oxidant O_2 content (d), but the effect on the fluidization might be too extensive. Instead, a better option could be to use the oxidant O_2 content as a feedforward signal to the flue gas O_2 control loop. Simulations for structures (c) and (d) with adequately tuned PID controllers can be seen in Figure 6, where a stepwise negative change to the secondary oxidant O_2 content setpoint was made at 100 time steps and a positive change to the primary oxidant O_2 setpoint at 300 time steps. Considering the oxidant and flue gas O_2 control performance, both structures performed similarly.

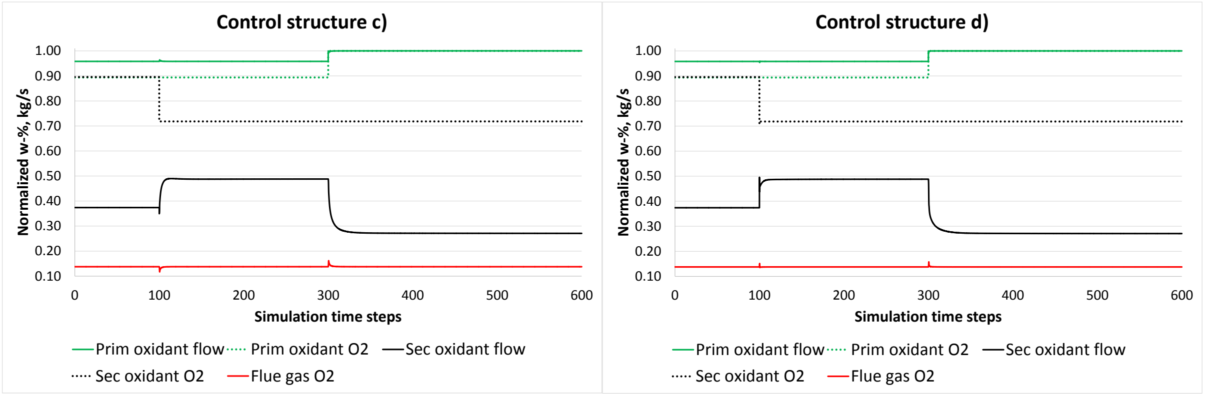

Figure 6. Normalized simulated flue gas and oxidant O_2 percentages and input oxidant flowrates for secondary oxidant O_2 (100 time steps) and primary oxidant O_2 (300 time steps) concentration setpoint changes with oxidant + flue gas O_2 control structures c) and d).

The concerns about fluidization illustrate that there might be a need to control the total input oxidant flowrates in oxy combustion. As there are five major input flows (fuel + limestone, primary/secondary pure O_2/RFG), three outputs can principally be controlled beside the necessary flue gas O_2 and heat generation (e.g. flue gas temperature or enthalpy) outputs. A combined flue gas O_2, oxidant O_2 and oxidant flow control structure (Figure 7) might be a good solution for the oxy-CFB. The total gas flowrates can be controlled either with the RFG or the total oxidant flows, but as the total oxidant also modifies the oxygen input, the latter option might lead to conflicts with e.g. flue gas O_2 control. For the fluidization, oxidant volume flows should preferably be used as controlled variables instead of mass flows due to potential gas density changes in oxy mode. Another option would be to use the fluidizing gas velocities directly, but these measurements are often not available in industrial boilers. While the gas velocity close to the grid can be approximated from the primary gas flow, the freeboard velocity depends on several factors. One option would be to estimate the velocities e.g. through Bayesian state estimation [17,18].

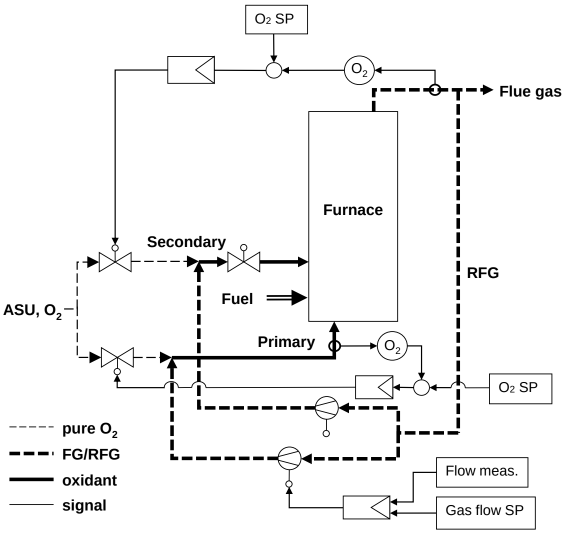

Figure 7. Concept example for oxidant and combustion control: combined flue gas O_2, primary oxidant O_2 & total input oxidant flow control. SP = setpoint.

One particular possibility for oxyfuel control is presented by the use of different oxygen concentrations for different oxidant inlets, i.e. oxidant O_2 staging. Changing the ratio of the primary/secondary oxygen supply alters the oxygen profile in the furnace, which shifts the combustion zones of the fuel. A high primary gas O_2 content prolongs the contact between the oxygen and the fuel, which has the potential to improve combustion efficiency, but also contributes to vertical temperature differences. An elevated secondary oxidant O_2 should contribute to a more even heat generation, but it might also increase the amount of flue gas heat loss and unburned fuel, although the latter concern is reduced in the CFB due to solids circulation. The effects of O_2 staging can partially be seen from Figure 8, where simulated oxygen and char combustion profiles for different primary/secondary oxidant O_2 ratios are shown.

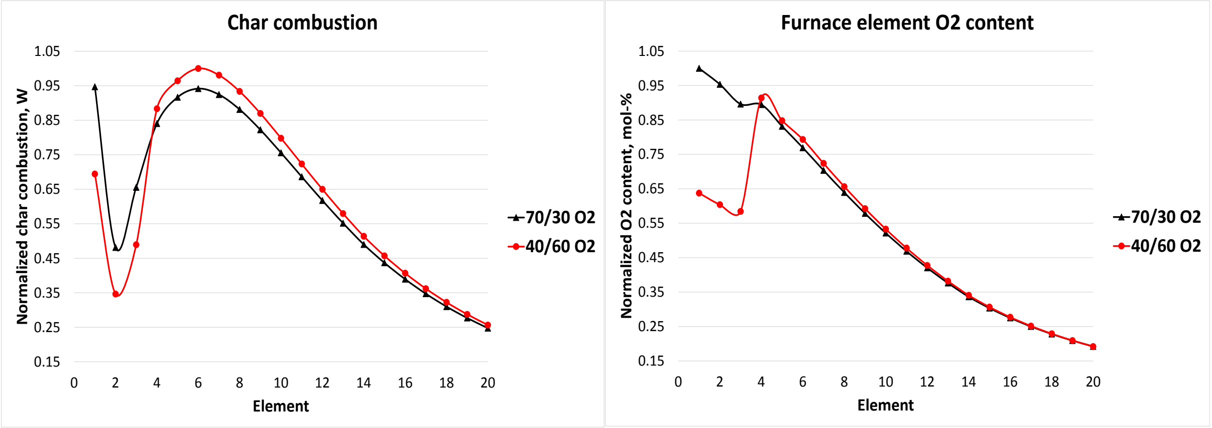

Figure 8. Simulated steady-state char combustion and furnace oxygen profiles for two different O_2 distributions (primary/secondary O_2 w-%) between the primary and secondary oxidant.

As the O_2 content of the primary oxidant was decreased in Figure 8, char combustion was reduced in the lower parts of the furnace, and vice versa. Volatile combustion occurred quite similarly in both cases (not depicted). In the simulations, RFG flows were altered during the O_2 staging changes to always keep the total primary and secondary gas flows constant. Alternatively, momentary RFG flow changes could be utilized e.g. to gain faster temperature transitions without affecting the O_2 input for the combustion. Notably, as long as the oxygen excess remains sufficient for complete combustion, a pure O_2 increase affects furnace properties in a similar fashion to the RFG, i.e. as a cooling and fluidizing medium. With an insufficient O_2 excess, temperature effects are less straightforward due to combustion changes.

If O_2 staging is used in oxy-CFB hotloop control, it should not interfere with other oxidant control systems. The benefits of oxygen staging largely depend on the steady-state furnace temperature profile and how important it is to obtain a steady heat transfer in the evaporator, especially considering that the CFB temperature profile is already more even than in many other combustion techniques due to the effective mixing and stored heat in the bed. For example, even though a clear change in the char combustion occurred in Figure 8, the corresponding changes in the furnace temperatures were significantly less notable. Although this might have been caused by the assumed ideally mixed calculation elements, the small size of the pilot or the low positioning of the secondary oxidant O_2 inlet in the furnace, the mixing in the bed might also be so effective that the possibilities for zone-wise temperature control through oxidant O_2 staging might be limited in practice. O_2 staging might serve a purpose for emission reduction.

4.2 Control structure synthesis through PRG analysis

It is evident that oxy combustion introduces a potential for a more complete control of the combustion process than air-firing. This was verified through the results of the PRG analysis, where control structures were synthesized for managing outputs that were selected based on the considerations of chapter 4.1 (Table 2). The controlled outputs were the primary oxidant O_2 content, the grid velocity, the flue gas O_2 content and temperature, and the furnace temperature in the middle of the riser. The manipulated inputs were the primary and secondary pure O_2 and RFG flows, and the fuel flow. Control structures were ranked based on beneficial and harmful PRG elements and the total average PRGs.

Table 2. ICI control configurations for the chosen outputs/inputs, furnace temperature control employed. Separate pure O_2 and RFG oxidant components were used for control.

	Inputs	Prim O2 flow	Prim RFG flow	Sec O2 flow	Sec RFG flow	Fuel flow		**Total candidates**
Outputs	**Input-output pairs**	**1**	**2**	**3**	**4**	**5**		120
Flue gas O2 content	**1**			🟩				
Flue gas temperature	**2**					🟩		
Furnace temperature, middle	**3**				🟩			
Dense bed velocity	**4**	🟨	🟩					
Primary oxidant O2 content	**5**	🟩	🟨					
			Total amount of PRG elements in the specified classes					
Rank by PRG	**ICI by PRG**	**NI values**	$0.9 \le PRG \le 1.2$	$0.1 \le PRG < 0.5$	$0.05 \le PRG < 0.1$	$0 < PRG < 0.05$	$PRG > 10$	**Total average PRG**
1	3 5 4 2 1	0.0946	12	0	0	0	0	1.9776
2	3 5 4 1 2	0.7182	13	13	0	0	0	1.9477

The PRG ICI calculations provided two control structures with good properties in terms of beneficial PRG values. Since the fuel feed was responsible for the heat generation in the furnace, it essentially determined the flue gas energy content and thus also its temperature. Rather expectedly, the flue gas O_2 was adjusted with the secondary pure O_2, and the secondary RFG could be utilized for furnace temperature control. The primary oxidant O_2 was adjusted with the primary oxygen or RFG flow, and the grid velocity with the respective other component. As was previously suspected, the first of these options was slightly better. The PRG values were even improved, when the primary and secondary RFG inputs were replaced with the respective total oxidant flowrates in the PRG analysis (Table 3). Despite the successful design results, the somewhat large RGA and PRG values of some input-output pairings (especially the Table 3 case) showcased that more than one input might have a similar effect on the selected outputs, although the systems were still far from being ill-conditioned.

Table 3. ICI control configurations for the chosen outputs/inputs, furnace temperature control employed. Pure O_2 and total oxidant gas flows were used for control.

	Inputs	Prim O2 flow	Sec O2 flow	Total prim gas flow	Total sec gas flow	Fuel flow		**Total candidates**
Outputs	**Input-output pairs**	**1**	**2**	**3**	**4**	**5**		120
Flue gas O2 content	**1**		🟩					
Flue gas temperature	**2**					🟩		
Furnace temperature, middle	**3**				🟩			
Dense bed velocity	**4**			🟩				
Primary oxidant O2 content	**5**	🟩						
			Total amount of PRG elements in the specified classes					
Rank by PRG	**ICI by PRG**	**NI values**	$0.9 \le PRG \le 1.2$	$0.1 \le PRG < 0.5$	$0.05 \le PRG < 0.1$	$0 < PRG < 0.05$	$PRG > 10$	**Total average PRG**
1	2 5 4 3 1	0.0437	26	0	0	0	0	2.3409

Both the Table 2 and Table 3 cases applied oxidant O_2 control only to the primary oxidant due to its importance for the oxygen supply and operational safety. ICI controllable solutions with secondary oxidant O_2 control could also be obtained by adding the total secondary gas flow to the available manipulated inputs, but the resulting ICI control solutions suffered from severe ill-conditioning, as both the individual RFG/pure O_2 components and the total flow of the secondary oxidant were used for control (not independent variables). Like the primary oxidant O_2 concentration, only the fluidization velocity close to the grid was included as a controlled output. However, if a more complete control of the gas velocity profile was desired, the furnace temperature output could be successfully replaced with the freeboard velocity in the control design (Table 4). Interestingly, this setup also generated ICI solutions, where the fuel flow was used for controlling fluidization velocities, possibly due to the temperature effects on the gas volumetric flowrates from an altered fuel firing power. These control solutions would be infeasible in practice, which was also observed as poor PRG element values. In general, the PRG values of the Table 4 control structures were closer to the ideal value 1 than in Tables 2-3. This indicated that the furnace temperature was influenced by more factors than the fluidization velocity.

Table 4. ICI control configurations for the chosen outputs/inputs, freeboard fluidization control employed. Pure O_2 and total oxidant gas flows were used for control.

	Inputs	Prim O2 flow	Sec O2 flow	Total prim gas flow	Total sec gas flow	Fuel flow		**Total candidates**
Outputs	**Input-output pairs**	**1**	**2**	**3**	**4**	**5**		120
Flue gas O2 content	**1**		🟩					
Flue gas temperature	**2**			🟨		🟩		
Freeboard velocity	**3**				🟩	🟨		
Dense bed velocity	**4**			🟩	🟨	🟧		
Primary oxidant O2 content	**5**	🟩						
			Total amount of PRG elements in the specified classes					
Rank by PRG	**ICI by PRG**	**NI values**	0.9 ≤ PRG ≤ 1.2	0.1 ≤ PRG < 0.5	0.05 ≤ PRG < 0.1	0 < PRG < 0.05	PRG > 10	**Total average PRG**
1	2 5 4 3 1	0.2365	35	0	0	0	0	1.3393
2	2 3 5 4 1	105.0803	24	13	5	0	2	1.8353
3	2 3 4 5 1	3.0010	21	11	3	11	0	1.1934

5. Conclusions

This work investigated the different control possibilities for oxy combustion in circulating fluidized bed boilers (CFB). Oxy-firing causes several changes in the boiler dynamics and gives an added degree of freedom for combustion control due to the separate pure O_2 and recirculated flue gas (RFG) oxidant flows. Based on structural analysis and dynamic simulations with a combustion side hotloop model, special considerations are required in the CFB for oxidant control configurations, especially for the secondary gas. Selecting the right manipulated variables for flue gas O_2 control is a tradeoff between obtaining fast responses and altering fluidization and cooling in the bed according to disturbances. Special attention should be paid on whether flue gas O_2 disturbances generally affect the combustion heat generation or not. The chosen flue gas O_2 control structure affects oxidant O_2 control possibilities, although pure O_2 flows should preferably be used for this task especially for the primary oxidant. Oxidant O_2 staging has the potential to improve furnace profile control in oxy-firing, but its usefulness for the CFB might be limited and thus needs to be examined more thoroughly.

Since the separate pure O_2 and RFG flows lead to more control possibilities in oxy combustion compared to air-firing, plantwide control structure design was performed for the oxy-CFB with the partial relative gain (PRG) method based on the concept of integral controllability with integrity (ICI). The results showed that ICI controllable control structures could be obtained, in which the flue gas O_2 percentage, the oxidant O_2 percentage, the flue gas temperature, fluidization velocities and furnace temperatures could be controlled with the available fuel and gaseous flow inputs. In terms of the used metrics, the best ICI solutions had good properties, although a few larger relative gain values also hinted the interconnected nature of the chosen furnace variables. For this reason, the importance of design methods like interaction analysis increases in oxy combustion control synthesis.

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