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Self-optimizing control structure design in oxy-fuel circulating fluidized bed combustion

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ABSTRACT

A wealth of control designs and experience are available for traditional air combustion in circulating fluidized bed (CFB) boilers. For the novel process of oxy combustion (for facilitated CO_2 capture) input gas compositions and flows can be adjusted independently, which decouples fluidization and oxygen carrying tasks and introduces new degrees of freedom and alternatives for control. The self-optimizing control approach (as formulated by Skogestad and colleagues in the 2000s) was used with steady-state approximations of a validated dynamic model for a pilot-size CFB combustor to study how the added degrees of freedom should be used. Instead of centralized online optimization of setpoints, self-optimizing control searches for a set of controlled variables which can be kept at constant setpoints despite disturbances and measurement errors, resulting in performance with acceptable steady-state loss. Results for air firing support method validity by suggesting the common practice in control; keeping power, flue gas O_2 and primary air/fuel feed ratio constant. For oxy firing, various control structures could satisfactorily compensate for studied disturbances and errors. Results suggest direct oxidant O_2% control or simpler feed-forward solutions in line with current industrial CFB control, or alternatively using the added degrees of freedom for controlling variables such as furnace temperatures. Differences in, e.g. controllability, dynamic performance and implementation cost are relevant in further studies. The results serve as a first step in oxy-CFB control studies, suggesting candidate structures for dynamic analysis.

1. Introduction

This paper describes the application of self-optimizing control approach in control structure design of a circulating fluidized bed (CFB) boiler that can be operated in both air and oxy combustion modes.

In oxy combustion, the combustion process is modified to produce flue gas very rich in CO_2 which facilitates the CO_2 capture. This is done by replacing combustion air with oxidant, a synthetic mixture of high-purity oxygen and recycled flue gas (RFG) which acts as an inert thermal diluent. Main flue gas compounds are CO_2 and H_2O with a small amount of other gases (such as O_2, N_2, Ar, NO_x and SO_x), and CO_2 is ready for sequestration after drying and impurity removal. The change of gaseous environment in furnace affects, e.g. combustion, gas properties and heat transfer.

There are two design options for oxy combustion plants. Greenfield oxy combustion boilers can be designed to operate under very high oxidant O_2 percentage (up to 60%) and high temperature, which improves efficiency and significantly reduces boiler volume for the same output (example of CFB in Leckner and Gómez-Barea, 2014) or, alternatively, significantly increases boiler output for same boiler size. Current research has mostly covered the other option of first-generation, ready-to-convert, dual-firing and retrofit boilers, where the aim is to approximate air firing conditions so that air and oxy firing can be used in the same boiler. This dual-firing option enables startups and shutdowns in air firing mode and provides operational flexibility that can be used to disconnect ASU/CPU, e.g. due to process malfunction or to maximize plant net output for peak power or grid frequency control participation. Buffer tanks for O_2 and flue gas may also be used for enhanced flexibility.

In their landmark reviews on oxy combustion of solid fuels, Buhre et al. (2005), Wall et al. (2009) and Toftegaard et al. (2010) thoroughly describe the issues related to the oxy combustion process, combustion fundamentals and emission formation, with main focus in pulverized coal (PC) combustion. Scheffknecht et al. (2011)

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Nomenclature

Nomenclature and abbreviations

CFB	circulating fluidized bed (combustion)
PC	pulverized coal (combustion)
IPCC	Intergovernmental Panel on Climate Change
CCS	carbon capture and storage
BECCS	bio-energy and CCS
RFG	recycled flue gas
ASU	air separation unit for oxygen production
CPU	CO_2 compression and purification unit
CV	controlled variable
MV	manipulated variable
MPC	model predictive control
PID	proportional integral derivative (control)

***matrix/vector**, scalar, variable, descriptive term*

$\boldsymbol{u}$	inputs, manipulated variables
$\boldsymbol{y}$	output
c_n	control configuration, CV set, $n = 1, 2, \ldots, C$
d_n	disturbance, $n = 1, 2, \ldots, D$, d_1 = nominal case
i_n	implementation error, $n = 1, 2, \ldots, I$, i_1 = nominal case
$J(c,d,i)$	cost for given CV set, disturbance and implementation error
$L(c,d) = J(c,d) - J_{opt}(d)$	loss for given CV set and disturbance
g	constraints
$\boldsymbol{u}_{opt}(d)$	optimal u for disturbance d
$\boldsymbol{y}_{opt}(d)$	optimal y for disturbance d
$J_{opt}(d)$	optimal cost for disturbance d
w	mass fraction (0–1)
$\dot{m}$	mass flow rate
$\dot{V}$	volume flow rate
$w_{O_2}^{fg}$	notation example, concentration of component (subscript) in flow (superscript)

Super/subscripts

fuel	fuel
fg	flue gas
PO	primary oxidant
SO	secondary oxidant (multiple injection points)
RFG	recycled flue gas

Ratio example

$\dot{m}^{PO}/\dot{m}^{fuel}$ ratio of PO/fuel mass flow

Temperatures and densities

T_1^{bed}	temperature in bed at level 1 (1–20)
ρ_1^{bed}	density in bed at level 1 (1–20)

Fluidization velocity

v_f fluidization velocity above grid

Output power

$\dot{Q}^e$	evaporator power, heat flux from evaporator to steam cycle [kW]
$\dot{Q}^{fg}$	estimate for heat from recovery section [kW]

Cost function

$j_{element}$	cost coefficient for element
$J_{element}$	cost for element [€/s]
$J, J(d, c)$	total cost, sum of element costs, [€/h] (profit equals negative cost)

present circulating fluidized bed combustion as an attractive option to PC. Oxy combustion effects are considerably different for these two combustion technologies, which must be carefully noted.

CFB boilers are drawing attention in oxy combustion due to their inherent advantages in fuel quality tolerance and fuel flexibility (important for low rank coal, biomass and fuel mixes), efficient combustion and long residence times, relatively easy emission control (in-furnace sulfur capture with limestone, low NO_x formation and hydrocarbon emissions), relatively low furnace temperature, uniform heat flux profile and possibility to control bed temperature with immersed heat exchangers (e.g. Myöhänen et al., 2009). CFB size has increased over the last decades to 500–600 MW scale, making it an option for large-scale utility use. Foster Wheeler 460 MW_e air-fired CFB with supercritical once-through steam generation in Lagisza, Poland, has been operational from 2009 (e.g. Ostrowski and Goral, 2010). In the recent IPCC report 2014 (IPCC, 2014), combining bio-energy and CCS (BECCS) is presented as one of the few technologies capable of removing past CO_2 emissions from the atmosphere.

In their overview on current state-of-the-art, Anthony and Hack (2013) point out that oxy combustion was first suggested for bubbling fluidized bed combustion already in the 1970s. Recently, oxy combustion in CFB boilers has been investigated and piloted by several companies, for example Foster Wheeler, CANMET and Endesa/CIUDEN (Eriksson et al., 2007, 2009; Hack et al., 2008; Myöhänen et al., 2009; Kuivalainen et al., 2010; Hotta et al., 2012; Lupion et al., 2013), Alstom (ya Nsakala et al., 2004; Suraniti et al., 2009) and Metso (Varonen, 2011; Varonen et al., 2012). Research on oxy-CFB have covered areas such as combustion characteristics (Czakiert et al., 2006; Krzywanski et al., 2010a,b; Duan et al., 2011), operational viewpoints (Romeo et al., 2011; Gunther et al., 2013; Leckner and Gómez-Barea, 2014) emission formation and control (Duan et al., 2011; Lupiáñez et al., 2013; Rahiala et al., 2014; Krzywanski et al., 2015), ash, agglomeration and slagging (Wu et al., 2011), heat transfer (Seddighi Khavidak et al., 2015) and CFD modeling (Zhou et al., 2011). Test rigs and pilot-size facilities have been utilized in studies (Jia et al., 2007; Romeo et al., 2011; Czakiert et al., 2011; Duan et al., 2011; Tan et al., 2012; Seddighi et al., 2013; Zhou et al., 2014). Dynamic tests and simulations based on the 20–100 kW_{th} pilot equipment at VTT, Finland have recently been reported by Hultgren et al. (2014) and Lappalainen et al. (2014), both with special focus on operational decisions and control issues during air–oxy switching.

Oxy combustion is technologically feasible and demonstrations have been commenced within several large projects (overview in Wall et al., 2011). The 30 MW_{th} oxy-CFB demonstration plant (Lupion et al., 2013) at Endesa/CIUDEN CCS test facility in Spain (built under the EU-FP7 program) was commissioned in 2011. However, plans for large scale or full-size plants have not been realized so far. Non-technical barriers such as regulation and public acceptance are often considered to be of larger significance for CCS commercialization than technical issues. In case of oxy combustion, the auxiliary processes required for O_2 production in an air separation unit (ASU) and CO_2 processing and purification unit (CPU) for sequestration can be built based on existing well-established technology. Large-scale oxygen production with cryogenic distillation is a very energy intensive process. Thus the auxiliary processes involve efficiency penalty in form of reduced net power output (7–11%-points drop in efficiency, e.g. Toftegaard et al., 2010) and the use of CCS must be justified by, e.g. high-price or limited CO_2 emissions. Recent research on oxy combustion has covered improving efficiency with, e.g. careful plant-wide process integration (Kotowicz and Balicki, 2014; Skorek-Osikowska et al., 2013) and advanced oxygen production methods such as membrane-based technologies (Skorek-Osikowska et al., 2015). Commercial whole-chain modeling tools have also been developed to address