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ANALYSIS OF THE TRANSITION TIME FROM AIR TO OXY-COMBUSTION

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In this paper some issues of the transition process from air- to oxy-combustion were investigated. Advantages of flexible combustion were described. Flexible combustion tests carried out at four European plants and five plants outside Europe of different scales of process and test parameters were presented. An analysis of the transition time from air to oxy-combustion of different laboratory and pilot scale processes was carried out. The "first-order + dead time" approach was used as a model to describe transition process. Transitional periods between combustion modes and characteristic parameters of the process were determined. The transition time depends not only on the facility's capacity but also it is impacted by specific operational parameters.

Keywords: oxy-fuel, combustion, dynamic transition

1. INTRODUCTION

Oxy-fuel combustion is recognised as technology which can be integrated with carbon capture and storage/usage (CCS, CCU). Moreover, the process can decrease emissions of gaseous pollutants, especially if nitrogen oxides (NOx) are taken into account (Jankowska et al., 2014; Toftegaard et al., 2010) Currently, the application of oxy-fuel technology in big-, industrial-scale is still being discussed and considered. The construction of new oxy-fuel boilers is taken into account, although retrofitting an existing power plant to an oxy-firing system (Fei et al., 2015; Fry et al., 2011) provides another solution. Moreover, it can be said the most possible solution is to develop a technology that will be able to be operated simultaneously under air- and oxy-fuel modes. This idea, proposed by Foster Wheeler company and researchers from Czestochowa University of Technology, is known as Flexiburn^{TM} technology (Eriksson et al., 2009; Lupion et al., 2011; Nowak, 2010; Seltzer et al., 2009). Flexiburn^{TM} is an organisation of a combustion process enabling to conduct fluent transition between air- to oxy-fuel combustion and inversely, without blowing out the combustion chamber (sometimes called withdrawal or shutdown of the boiler).

The process of transition between air- and oxy-fuel modes is currently being investigated by few research groups (Duan et al., 2014; Hultgren et al., 2014; Jia et al., 2012; Lupion et al., 2013; McCauley et al., 2009; Mine et al., 2013; Tan et al., 2012). Usually, researches focused on the transition rate. However, Flexiburn^{TM} was also applied as a scientific tool to investigate NO conversion during oxy-fuel combustion (Lasek, et al., 2012; Lasek et al., 2013). Very recently Luo et al. (2014) simulated the transition process (between air- into oxy-combustion) in a 3 MWth oxy-fuel test facility using Aspen Plus Dynamics software.

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Potentiality of flexible transition between combustion modes is crucial for large scale industrial plants, where every shutdown of the plant is connected with production loss and technological risk. Such a possibility of transition allows the plant to be independent of continous oxygen demand. If any of oxy-fuel specific systems goes offline, plants can continue to operate in air-fired mode (Zheng, 2011). Summarizing, the technique allows to use the advantages of oxy-fired combustion with the versatility of air-fired combustion and creates an excellent tool for comparing both processes at identical technological conditions. The aim of this paper is to analyse the transition process from air- to oxy-fuel mode. Especially, the rate of transition is taken into account and changes in CO_2 concentration is considered. To the best knowledge of the authors, it is the first time when the transition process is analysed for all available data from different-scale combustion facilities.

2. METHODOLOGY

2.1. Characteristics of selected experimental facilities used in the analysis

In this paper the Flexiburn^{TM} process was analysed for different experimental facilities. The particular analysis was carried out for four facilities of different scales (capacities) and different fuels: two tests in a CFB reactor (circulating fluidised bed reactor), one in a BFB reactor (bubbling fluidised bed reactor) and one in a FCC reactor (fluid catalytic cracking reactor). Table 1 shows a comparison of the facilities. Laboratory and Process Development Unit (PDU) scale tests were carried-out in Institute for Chemical Processing of Coal (IChPW), Poland. The lab-scale facility has the capacity of 0.7 kg/h. The process parameters are presented in Fig. 1 and its caption 1. A test was also carried out using a completely new (commissioned in 2013) testing plant for pressurised gasification and oxy-combustion of solid fuels in Circulating Fluidised Bed, in PDU scale at fuel flow 14 kg/h, inlet composition of oxy-fuel oxidant: 20 v.% O_2, 80 v.% CO_2, outlet composition: 7 v.% O_2, 80 v.% CO_2, overpressure of 3.6 bar. Both units belong to the Clean Coal Technology Center (IChPW, Zabrze). During the Flexiburn^{TM} test the following experimental procedure was applied. Before each experiment, silica sand was introduced into the reactor and heated (in an air stream) to 800°C by an external heat source (electrical heating elements or gas-burner in case of lab-scale or PDU scale facility respectively) until steady-state

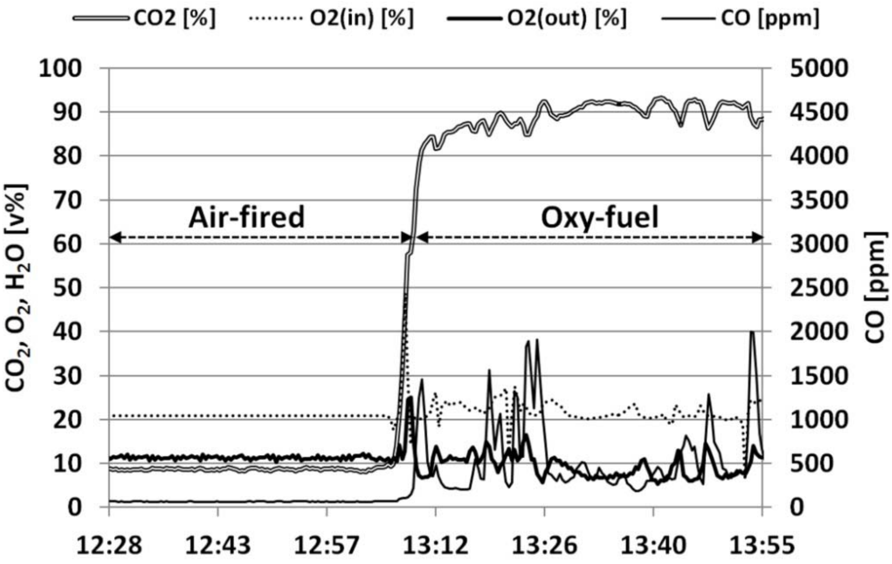

Fig. 1. Measured composition of flue gas composition during transition process between air- and oxy-fuel mode (Ziemowit coal, inlet composition of oxy-fuel oxidant: 20 v.% O_2, 80 v.% CO_2; total pressure of 2.4 bar; fuel feed of 0.72 kg/h), cited from (Lasek et al., 2013), permission of Elsevier publisher, License No. 3573030349468

conditions were reached. After this operation, proper amounts of coal and air were continuously introduced into the combustion zone, and the heating elements were turned off. After coal was introduced, the temperature was maintained to obtain steady state conditions. After this period the oxidant was changed from air- into CO_2/O_2 mixture. It was carried out by closing the air valve (from a compressor) and opening CO_2 and O_2 valves (from gas cylinders). An example of measuring the flue gas composition is presented in Fig. 1. A detailed description of the experimental facility is presented elsewhere (Lajnert and Latkowska, 2013; Lasek, et al., 2012; Lasek et al., 2013).

The third facility (a fluid catalytic cracking reactor) was built in Brazil for Vacuum Gasoil (VGO) cracking, in a pilot scale with the capacity of 150 kg/h. A liquid fuel was fed with a solid fuel (hard and brown coal) into the oxy-fuel combustion chamber. The fourth and the biggest of all presented facilities is a pilot-scale CIUDEN Oxy-CFB Boiler, with the capacity over 5 Mg/h, located in Spain. Table 1 lists information about other facilities. These facilities (bottom part of the Table 1) were also analysed. However, due to a lack of data only transition time was estimated in their case.

2.2. Theoretical analysis of the transition time from air to oxy-combustion

Very often unsteady state processes are modelled using a “first-order + dead time” approach. In control theory, the model is described by the Laplace transform variable, in the form of $G(s) = K_p\exp(-\Theta s)/(\tau_p s+1)$ (Bequette, 2003). However it is possible to determine the model as a function of time (see Eqs. 1). This approach is often applied for a description of dynamic behaviour of energy units like heat exchangers (Kirtania, 2012) or boilers and combustion chambers (Lasek et al., 2013; Shi et al., 2012). A model of the transition process is described by Eq. (1) (Lasek et al., 2013):

$$\begin{aligned} t < \Theta, &\quad N_{\mathrm{CO2}}(t) = 0 \\ t \geq \Theta, &\quad N_{\mathrm{CO2}}(t) = K\left\{1 - \exp\left(-(t - \Theta)/\tau_p\right)\right\} \end{aligned} \tag{1}$$

Factors Θ and τ are “dead time” and time constant, respectively. They were determined from experimental results using the method of least squares. „Dead time” begins at the moment when the force parameter changes the combustion regime. For example, it can be a valve that introduces CO_2/O_2 mixture and closes air flow to the combustion chamber. “Dead time” ends at the moment of a significant increase in CO_2 concentration at the combustor outlet. Θ (“Dead time”) equals a few minutes in all four cases. In fact, the applied model assumed that a step change of the control parameter (inlet parameter) gives a response of the outlet parameters. For a big scale experimental facility the step change of inlet parameter is sometimes problematic due to valve dynamic limitation, as well as safety and process stability issues. However, the presented model, assuming and determining the type of change is very useful from the practical point of view.

In the model change of CO_2 the concentration at the combustion chamber outlet was analysed. To compare results from different combustion chambers and different conditions the CO_2 real concentration was normalised to the form of N<0.1> according to Eq. (2) (Lasek et al., 2013):

$$N_{\mathrm{CO_2}}(t) = \frac{C_{\mathrm{CO_2}}(t) - \bar{C}_{\mathrm{initial\ CO_2}}}{\bar{C}_{\mathrm{final\ CO_2}} - \bar{C}_{\mathrm{initial\ CO_2}}} \tag{2}$$

$C_{CO2}(t)$ is the actual measured concentration of CO_2 as the function of time and “initial” and “final” are assigned to the average concentrations at the beginning and at the end of the Flexiburn^{TM} process, meaning in practice minimum and maximum concentrations. A comparison of the model and experimental results is shown in Fig. 2. Factors Θ (theta) and τ (tau) on the graph concern a test carried out using the facility with the BFB reactor. Fig. 1 presents characteristic curves for all four tests based on real process data (solid line) and model curves (dashed line).

Table 1. Simplified description of the analysed facilities

Research facility	Institution (research group)	Estimated transition time between air- and oxy-combustion	Type of transition	Test fuel type	Mean fuel flow rate during test	Lit.
BFB reactor	Institute for Chemical Processing of Coal, Zabrze, Poland	20 min	step	Polish coal Ziemowit	0.7 kg/h	Lasek et al. (2013)
CFB reactor		50 min	extended in time	Polish brown coal Bełchatów	14 kg/h	This research
FCC reactor	Petrobras, Rio de Janeiro, Brasil; Petrobras, Paraná, Brasil; Saipem S.p.A. (Eni Group), Italy	4 h	step	Vacuum Gasoil (VGO) / Heavy oil fractions	150 kg/h	de Mello et al. (2013)
CIUDEN Oxy - CFB Boiler	CIUDEN Technology Centre, Leon, Spain; Foster Wheeler ES, Spain	40 min	no data	Spanish anthracite coal (Cupo del Birzo)	5 469 kg/h	Hack et al. (2012)
30 MW Coal boiler	Callide A Power Station, Australia	1 h	step	Callide coal	No data	Yamada (2012)
4 MW coal test facility with horizontal furnace with a single burner	Babcock-Hitachi K.K. (BHK), Japan	30 min	extended in time	Bituminous coal from Australia	400-500 kg/h	Mine et al. (2013)
3 MW pilot scale boiler	Victoria, Australia	10 min	step	Victorian Brown Coal from Australia	No data	Zhang et al. (2013)
0,8 MW Oxy-fuel CFBC unit	CanmetENERGY, Canada	45 min	extended in time	Pine Bend coke	44 kg/h	Zheng (2011)
		45 min		Bituminous coal	54 kg/h	Tan et al. (2012)
		20 min		35% wood 65% coal	87 kg/h	Tan et al. (2013)
50 kW CFBC with warm flue gas recycle	Southeast University, China	1 h 20 min	extended in time	Bituminous coal/petroleum coke	5-8 kg/h	Duan et al. (2014)
3 MW	State Key Laboratory of Coal Combustion (SKLCC), Huazhong University of Science and Technology (HUST), China	30 min	extended in time	Chinese hard coal	420 kg/h	Zheng (2013), Luo et al. (2014)

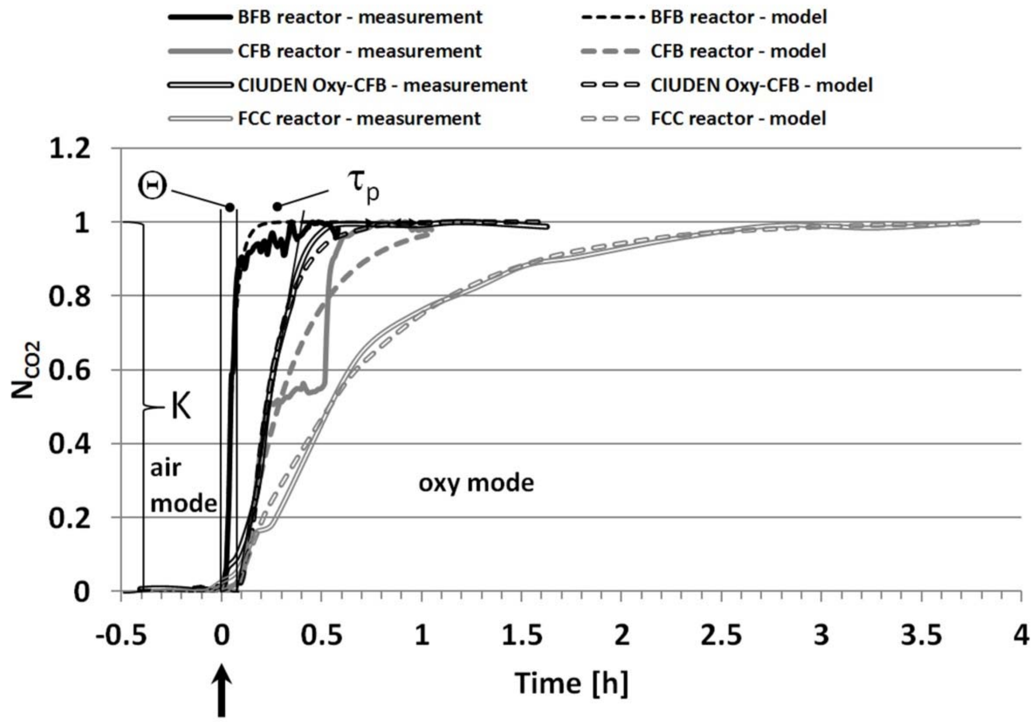

Fig. 2. Flexiburn^{TM} process for four facilities – normalized CO_2 flow output against time

Generally, a higher rate of CO_2 concentration change is characteristic for a facility of smaller capacity. Although the incompletness of process data reported in the literature (de Mello et al., 2013; Duan et al., 2014; Hack et al., 2012; Mine et al., 2013; Lasek et al., 2013; Tan et al., 2012; Tan et al., 2013; Yamada, 2012; Zhang et al., 2013; Zheng, 2011) does not allow to determine dynamic parameters, the estimated values of the transition time are presented in Table 1. The estimated time of combustion mode transition is in the range of 20 minutes to 4 hours.

It can be seen in Fig. 1 that the curve resulting from actual measurements for the installation "CFB reactor" is not regular. This is caused by staging dosage of media to the process. At the beginning of the transition process a mixture of air and CO_2/O_2 was introduced into the reactor. Next, after around 0.5 hour from the beginning of transition, a “pure” CO_2/O_2 mixture was supplied to the combustion chamber. A comparison of the obtained dynamic parameters (Θ and τ) for four selected facilities is presented in Table 2.

The transition process was also tested in other technological facilities situated at different scientific institutions. Nevertheless, analysis of the results is difficult because the exact moment of the medium switch (from air- to oxy- mode) was not given. Additionally, no information was provided, if the switch of parameters, that forces the transition, was instant or time dependent (e.g. ramp force).

A test of a high power unit - 30 MW coal boiler of Callide A Power Station in Australia was described by Yamada (2012). The process was characterised by a relatively long transition time (about 1h). Mine at al. (2013) tested a 4 MW coal test facility with a horizontal furnace and a single burner in Babcock-Hitachi K.K. (BHK), Japan. The transition time between the air- and oxy-fuel mode(s) was around 30 minutes. Faster transition time (10 minutes) was observed for a 3 MW pilot scale boiler fed by brown coal (Zhang et al., 2013). Zhang et al. (2013) and also Tan et al. (2012, 2013) presented a 0.8 MW Oxy-fuel CFBC unit situated in CanmetENERGY, Canada. The transition time of this facility was, depending on the test, from 20 to ca. 45 minutes. Duan et al. (2014) showed the Flexiburn^{TM} test in a 50 kW CFBC facility with hot flue gas recycle located at Southeast University, China. The transition time from air- to oxy-fuel combustion was almost 1.5 h.

Table 2. Characteristic values for four described research facilities

Research facility	Institution (research group)	Delay constant Θ	Time constant τ
Laboratory station for oxy-fuel combustion and gasification under pressure - BFB reactor	Institute for Chemical Processing of Coal, Zabrze, Poland	0.023 h = 1.4 min	0.036 h
Testing plant for pressurised gasification and oxy-combustion of solid fuels in Circulating Fluidised Bed – CFB reactor		0.09 h = 5.4 min	0.279 h
Fluid Catalytic Cracking reactor - FCC reactor	Petrobras, Rio de Janeiro, Brasil; Petrobras, Paraná, Brasil; Saipem S.p.A. (Eni Group), Italy	0.062 h = 3.7 min	0.674 h
CIUDEN Oxy - CFB Boiler	CIUDEN Technology Centre, Leon, Spain; Foster Wheeler ES, Spain	0.126 h = 7.6 min	0.141 h

3. CONCLUSIONS

The transition time of process change from air- to oxy-fuel modes was analysed for different facilities. It can be concluded that usually longer transition time was observed for a larger facility. However, the transition time depends not only on the facility’s capacity but also it is impacted by specific operational parameters. For the analysed facilities the transition time was in the range from 20 minutes to 4 hours. The main goal during transition process is to obtain a flexible change of the combustion regime without shutting down the boiler. It is very important from the practical point of view. The application of oxy-fuel combustion in industry will be more realistic if a boiler is able to obtain a stable transition between air- and oxy-combustion mode.

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SYMBOLS

$K = 1$	proportional factor
N	concentration (standardised)
t	time, h

Greek symbols

Θ	delay constant, h
τ	time constant, h

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