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Characteristics modeling for supercritical circulating fluidized bed boiler working in oxy-combustion technology

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Abstract Among the technologies which allow to reduce greenhouse gas emission, mainly carbon dioxide, special attention deserves the idea of 'zero-emission' technology based on boilers working in oxy-combustion technology. In the paper the results of analyses of the influence of changing two quantities, namely oxygen share in oxidant produced in the air separation unit, and oxygen share in oxidant supplied to the furnace chamber on the selected characteristics of a steam boiler including the degree of exhaust gas recirculation, boiler efficiency and adiabatic flame temperature, was examined. Due to the possibility of the integration of boiler model with carbon dioxide capture, separation and storage installation, the subject of the analysis was also to determine composition of the flue gas at the outlet of a moisture condensation installation. Required calculations were made using a model of a supercritical circulating fluidized bed boiler working in oxy-combustion technology, which was built in a commercial software and in-house codes.

Keywords: Thermodynamic analysis; Oxy-combustion; Supercritical CFB boiler

1 Introduction

Oxy-combustion technology assumes combustion of coal (or other fuels) in the atmosphere of oxygen-rich oxidant. The main assumption of the technology is to eliminate nitrogen ballast from the process. As a result,

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the exhaust gases leaving the boiler consists mainly of carbon dioxide and water vapor [1,2]. The advantage of such a realization of the combustion process is the ability to reduce the energy consumption of CO_2 separation process [3,4]. The oxy-combustion technology can be implemented into existing system (by retrofitting) or can be the technology adopted within the framework of the green-field type project. In the first case it may be necessary to reduce the size of the boiler and realize the reorganization of the flue gases duct [5]. Regardless of the type of investment it is expected that in the first coal-fired units working in oxy-combustion technology, the combustion process will be realized at the share of oxygen not exceeding 30%. Only the development of technology, especially materials, will allow to exceed this level. Although the combustion process can be realized with oxygen content slightly higher than typical oxygen content in air, oxygen produced in already commercially available oxygen separation units can be delivered with purity of up to 100%. To reduce the share of oxygen in the combustion atmosphere it is necessary to implement the dilution of oxidant by the exhaust gases recirculated from the outlet of the boiler. Both, a share of oxygen in the oxidant supplied to the combustion chamber and a share of oxygen in technical oxygen delivered from the air separation unit (ASU) installation, are the basic quantities specific to this technology. These values will significantly affect the design and performance of the basic components of the integrated oxy-combustion systems. In the paper the results of the analysis of the influence of changing of these two quantities on the main characteristics of the oxy-boiler are shown. The analysis for green-field type project was realized.

2 Model of a supercritical circulating fluidized bed boiler working in oxy-combustion technology

To perform the analysis it was necessary to create a suitable model of a circulating fluidized bed boiler. The model was largely developed using a commercial GateCycle software for power plant processes [18]. At the stage of the adoption of assumptions for building of the model it was decided to use an available in software program library block of the fluidized bed boiler, which consists of: a furnace chamber (FCH), evaporator (EVAP), last section of steam superheater (SH II) and the last section of reheater (RH II). The radiant part of circulating fluidized bed (CFB) boiler ends with a particle separator. Scheme of the model is shown in Figs. 1, and 2

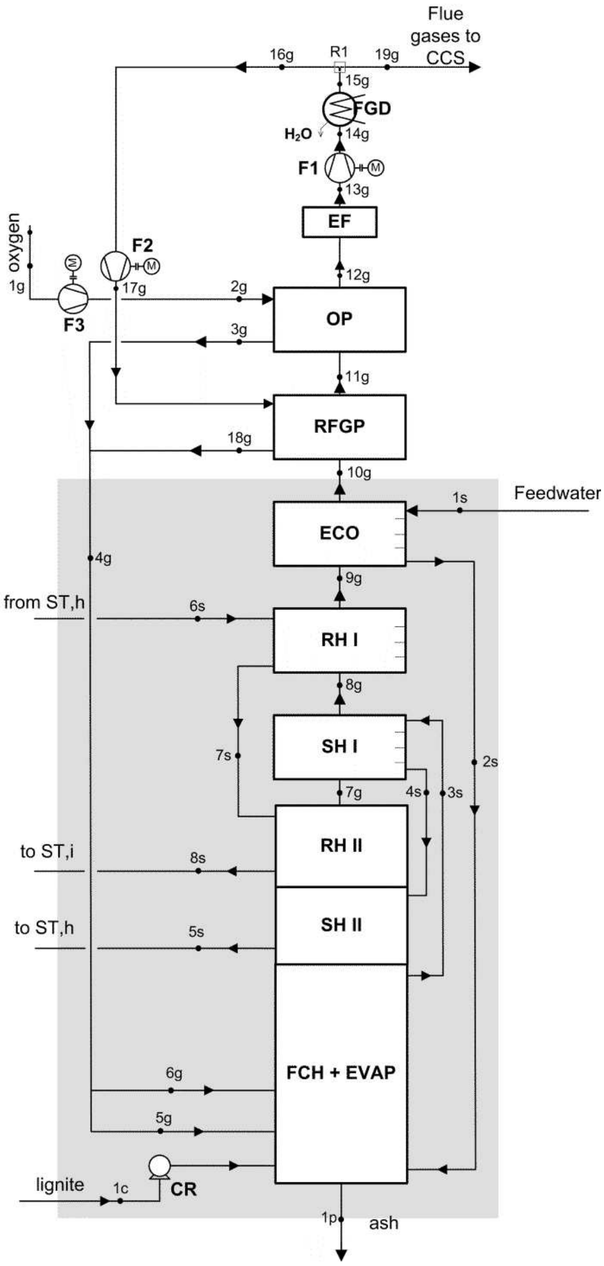

Figure 1: Scheme of a supercritical oxy-fuel CFB boiler: FCH – furnace chamber; EVAP – evaporator; SHI, SHII – superheaters; RHI, RHII – reheaters; ECO – economizer; RFGP – recirculeted flue gases preheater; OP – oxidant preheater; EF – electrostatic precipitator; FGD – exhaust gas dryer, F1,F2,F3 – exhaust, oxidant and recirculated flue gas fan, respectively; CR – lignite crusher; CCS – carbon capture and storage; ST – steam turbine; respectively: h – high pressure, i – intermediate pressure; indicies: s – steam, g – gas.

the profile of the oxy-fuel CFB boiler is presented. The model was described in detail in [6].

After the particle separator subsequent heat exchangers were placed. Successively, in the direction of the exhaust gas flow there are: the first section of superheater (SH I), first section of reheater (RH I) and the economizer (ECO). After leaving the economizer the exhaust gas stream exchanges heat in the recirculated flue gas heater (RFGP) and the oxidant preheater (OP).

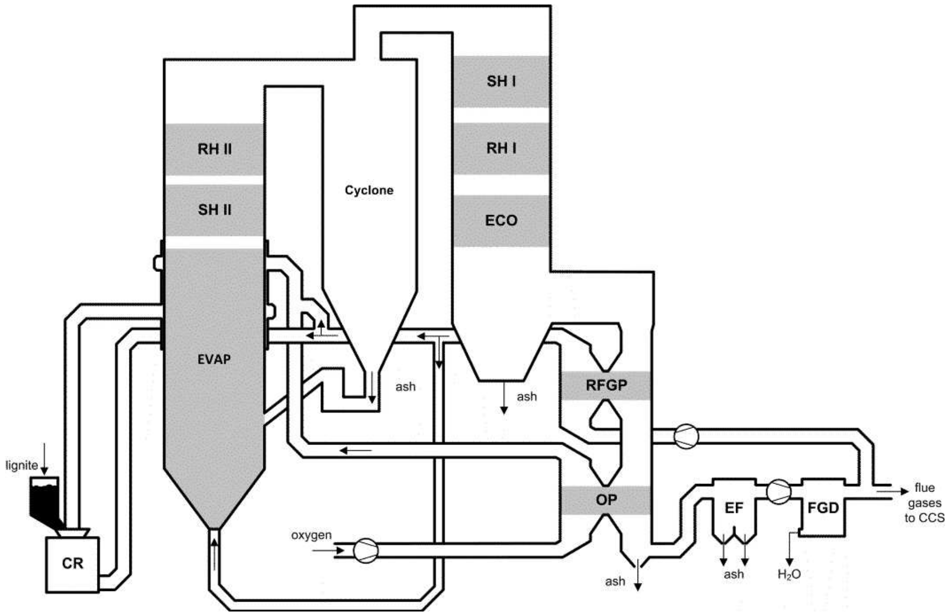

Figure 2: Profile of CFB boiler, other see Fig. 1.

3 Input data and computational algorithm

To determine the input data for the model of CFB boiler the results from the steam cycle model built in the commercial software presented in [7] were used. It was assumed that irrespective the values of the decision variables assumed for calculations the gross power of the power plant is equal to 600 MW. Also, the parameters of the steam (live steam 600 °C/29 MPa and reheated steam 620 °C/5 MPa) were maintained at a constant level. Key assumptions for the calculation of the CFB boiler model are presented in Tab. 1 [2,5,8], other assumptions were adopted on the basis of [7].

Table 1: Basic parameters of oxy-fuel CFB boiler.

Feed water temperature	t_1s	°C	297
Water temperature at the outlet from economizer	t_{2s}	°C	340
Steam temperature at the outlet from evaporator	t_{3s}	°C	480
Live steam temperature at the outlet from the boiler	t_{5s}	°C	604.9
Live steam flow	m_{5s}	kg/s	432.01
Reheated steam temperature at the outlet from the boiler	t_{8s}	°C	622.4
Reheated steam flow	m_{8s}	kg/s	365.65
Temperature difference at the cold side of economizer	$t_{5g}t_{1s}$	K	55
Oxygen temperature at the outlet from oxygen heater	t_{3g}	°C	220
Exhaust gas temperature at the outlet from flue gas heater	t_{18g}	°C	240
Live steam pressure at the outlet from the boiler	p_{5s}	MPa	30.1
Reheated steam pressure at the outlet from the boiler	p_{8s}	MPa	5.12
Oxygen content in mixture from air separation unit (rest is nitrogen)	$(O_2)_{ASU}$	%	95
Oxygen content in oxidant supplied to the combustion chamber	$(O_2)_{FCH}$	%	30
Oxidant excess ratio	λ	–	1.2
Moisture content in exhaust gas at the outlet from flue gas dryer	$(H_2O)_{9g}$	%	10

During the analysis the thermal efficiency of the boiler was determined from the following formula:

$$\eta_k = \frac{\dot{m}_{1s}(h_{5s} - h_{1s}) + \dot{m}_{6s}(h_{8s} - h_{6s})}{\dot{m}_c \, LHV} , \tag{1}$$

where:

$\dot{m}_{1s}, \dot{m}_{6s}$	–	live and reheated steam streams, kg s^{-1}
h_{5s}	–	enthalpy of a live steam at the outlet from the boiler, kJ kg^{-1}
h_{1s}	–	enthalpy of the feed water at the inlet to the boiler, kJ kg^{-1}
h_{8s}, h_{6s}	–	enthalpy of the reheated steam at the inlet and outlet of the boiler, kJ kg^{-1}
$\dot{m}_c$	–	stream of coal fed to the boiler, kg s^{-1}
LHV	–	lower heating value of coal, kJ kg^{-1}.

In the case where flue gases recirculation is not realized, the oxygen concentration in oxidant supplied to the furnace chamber would be equal to the concentration of oxygen in the oxidant produced in ASU [$(O_2)_{FCH} = (O_2)_{ASU}$]. Such organization of the combustion process and the reduction of the exhaust gas volume would allow to reduce the dimensions of the boiler but also, due to the very low share of inert gases, would cause a significant increase in a bed temperature. Therefore, in the first generation of oxy technology boilers it is planned to recirculate the proper amount of exhaust gas determined by the recirculation rate, which for the analyzed case is defined as

$$R_{R1} = \frac{\dot{m}_{16g}}{\dot{m}_{15g}} , \tag{2}$$

where:

$\dot{m}_{15g}$ – stream of exhaust gas leaving boiler, $\mathrm{kg\,s^{-1}}$

$\dot{m}_{16g}$ – stream of exhaust gas recirculated to the boiler, $\mathrm{kg\,s^{-1}}$.

Computational methodology in of the boiler assumes the determination of the mass flow of oxidant supplied to the boiler based on the feed water flow. The mass flow of oxygen supplied to the boiler from the air separation unit is determined at a level, which allows to maintain live and reheated steam streams at constant level. The oxidant mass flow consist of technical oxygen from the ASU installation and recirculated flue gases, which merges after, respectively: technical oxygen preheater (OP) and recirculated flue gases preheater (RFGP). Recirculated exhaust gas mass flow is maintained at the level, which allows to achieve preestablished concentration of oxygen in oxidant at the inlet to the combustion chamber [1].

Due to the constant temperature profile of the circulating medium in the boiler, it was necessary to change the exhaust gas temperature after cyclone to maintain a constant temperature difference in one point of the convective pass in the boiler. In the case of the concerned model, characteristic temperature difference is located at the cold side of feed water heater ($T_{10g} - T_{1s}$), and its value was set at 55 K.

During the analysis the decision variables were:

- oxygen share in the oxidant produced in ASU $(\mathrm{O2})_{ASU}$,
- oxygen share in the oxidant supplied to the furnace chamber $(\mathrm{O_2})_{FCH}$.

As it is shown in Tab. 1 the nominal values for these shares were 0.95 and 0.30, respectively. During the analyses, in the first phase, the value of the $(\mathrm{O_2})_{ASU}$ from 0.8 to 1.0 was changed while maintaining the value of $(\mathrm{O_2})_{FCH}$ at the nominal level. In the next stage of calculations the value of $(\mathrm{O_2})_{FCH}$ from 0.2 to 0.4 was changed while maintaining the value of $(\mathrm{O_2})_{ASU}$ at a nominal level. During the analysis the influence of changes of shares of oxygen on the characteristics of the boiler was investigated.

Among these characteristics there were the following: current adiabatic flame temperature, exhaust gas volumetric flow, boiler thermal efficiency and recirculation rate [9]. In the context of future integration of the boiler with CCS installation in the Section 4 the influence of a change of oxygen share on the composition of the gases leaving the boiler are presented.

4 Results of calculations

During the study of supercritical CFB boiler working in oxy-combustion technology an analysis of the influence of oxygen concentration in oxidant produced in ASU installation and oxygen concentration in the oxidant at the inlet to the combustion chamber at some important characteristics of this installation were made. In each of the figures: the characteristics as a function of $(O_2)_{FCH}$ are marked with a continuous line and with a dashed line the characteristics as a function of $(O_2)_{ASU}$ are marked. Results for similar studies, but carried out for pulverized oxy-boiler are shown in [10,11].

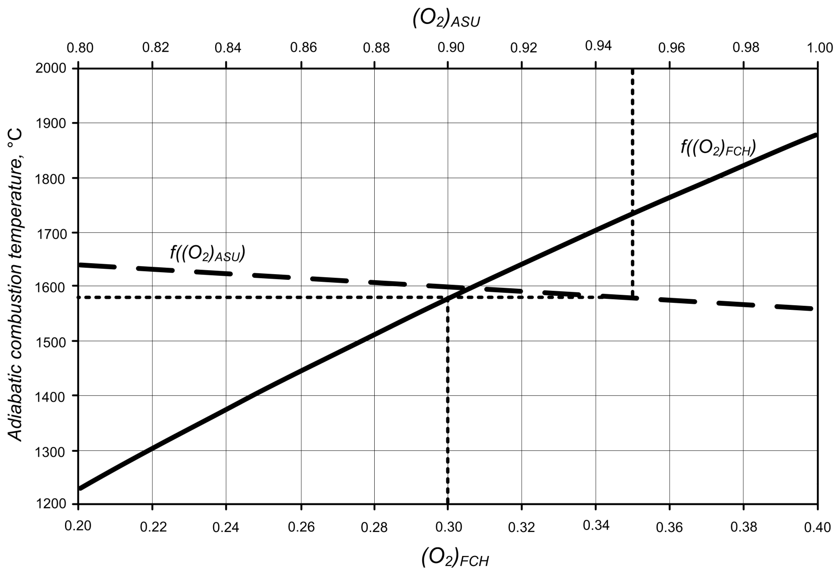

Figure 3: Adiabatic combustion temperature as a function of oxygen content in oxidant.

Figure 3 shows the characteristics of adiabatic combustion temperature in the boiler at the height of the combustion chamber. It was observed that with increasing share of oxygen in the oxidant supplied to the boiler, the temperature increases from 1220 to 1870 °C. Further increasing of the oxygen share can cause a problem related to the durability of the materials used for the evaporator, but also the problem with the circulating bed. An increase of $(O_2)_{ASU}$ contributes to the slight drop in the adiabatic temperature.

The increase of oxygen share in oxidant supplied to the furnace chamber causes a significant decrease of volumetric flow of exhaust gases leaving the boiler. Therefore, to ensure the optimum gas velocity in the case of higher values of oxygen share the cross surface of the flue gases duct of boiler should be decreased. Maintaining an appropriate flow velocity is important both for providing the adequate heat transfer conditions, but also for ensuring the fluidization conditions. The change of oxygen share in oxidant produced in ASU does not provide a significant change of values of flue gases flow velocity. Respective results of analysis are shown in Fig. 4. With a gradual increase of the content of oxygen in oxidant at the inlet to the boiler, a reduction of the exhaust gas volume was observed, which has also been identified as a result of the increase of adiabatic combustion temperature in the chamber.

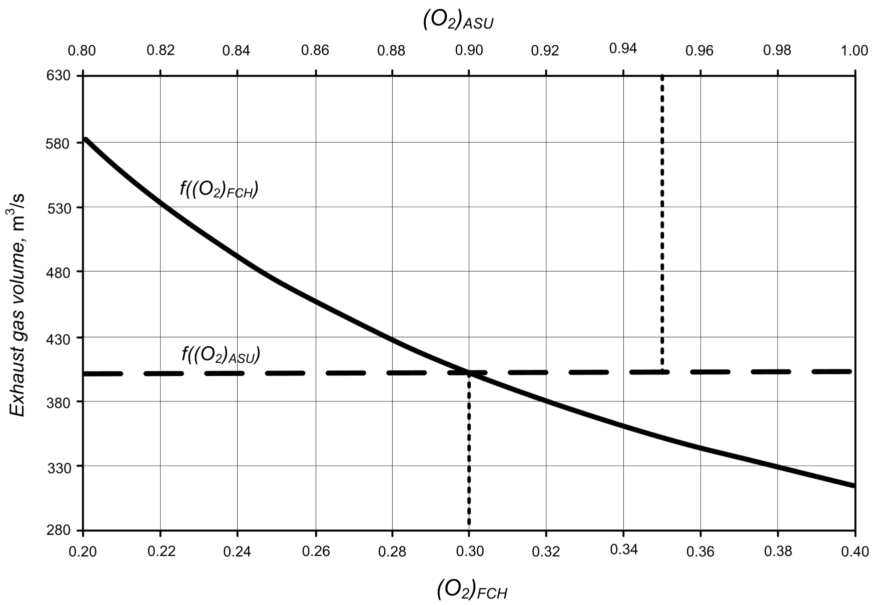

Figure 4: Exhaust gas volume as a function of oxygen content in oxidant.

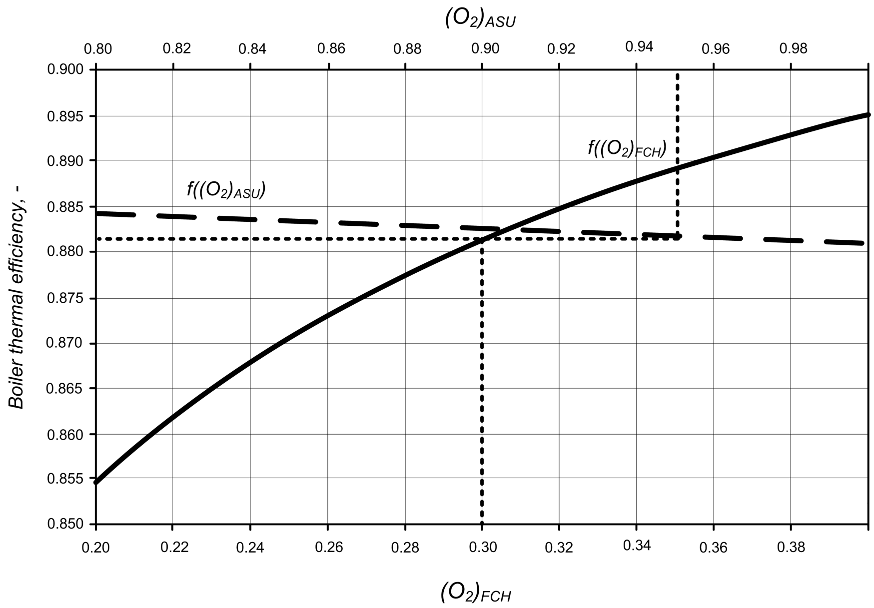

Figure 5: Boiler thermal efficiency as a function of oxygen content in oxidant.

As a result of the conducted studies, in Fig. 5, characteristics of the boiler thermal efficiency as a function of analyzed concentrations were shown. Increase of efficiency with increasing oxygen concentration in oxidant at the inlet to the combustion chamber is a direct result of decreasing the outlet heat losses, which decreases with decreasing volumetric flow of exhaust gas leaving the boiler. Simultaneously, with the increase of adiabatic combustion temperature heat losses by radiation and with liquid slag also increases, but those losses do not have such a large influence on the overall efficiency as the outlet heat losses.

In Fig. 6. there was observed that with the higher desired $(O_2)_{FCH}$ decreases the recirculated exhaust gas flow necessary to supplement the nitrogen, and the recirculation rate varies from 0.82 for the oxygen concentration of 0.20 to 0.62 for the oxygen concentration equal to 0.40. The increase of $(O_2)_{ASU}$, and thus the reduction of the amount of inert gas which is nitrogen causes the necessity of increasing the recirculation rate.

In case of oxy-combustion technology it seems to be particularly advantageous to connect steam cycle with the installation of carbon dioxide sequestration from flue gas, its preparation for transport and subsequent storage. During the studies of the boiler the change of the exhaust gas

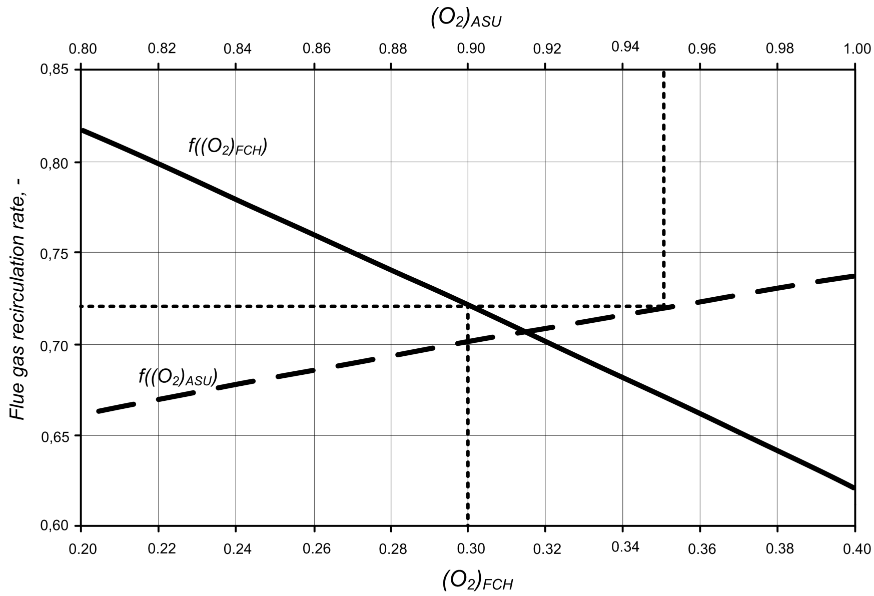

Figure 6: Flue gas recirculation rate as a function of oxygen content in oxidant.

composition after flue gas dryer as a function of oxygen concentration in oxidant at the inlet to the combustion chamber changes was also analyzed (Fig. 7a). In Fig. 7b. the influence of a change of oxygen concentration in oxidant produced in ASU on the exhaust gas concentration is shown. It was observed that with increasing concentration of oxygen in the oxidant decreases concentration of CO_2 in the exhaust gas leaving the boiler, while increases the concentration of oxygen [12,13,14]. The contents of other exhaust components do not change significantly. Taking into consideration the obtained concentration of CO_2 in the context of the power consumption of the separation process the reduction of the oxygen concentration in the furnace chamber should be sought [15]. However, the power consumption will be determined by the volumetric flow of exhaust gas, which, as shown in Fig. 4, has the lowest value obtained for $(O_2)_{FCH} = 0.4$.

The last stage of analysis was the determination of auxiliary power of the machines working in the area of CFB as a function of oxygen share in the oxidant supplied to the furnace chamber. The results of the analyses are shown in Fig. 8. Due to the low sensitivity of the auxiliary power on the change of oxygen in the oxidant produced in ASU the results of respective analyses are not shown. With an increase of oxygen share in the oxidant

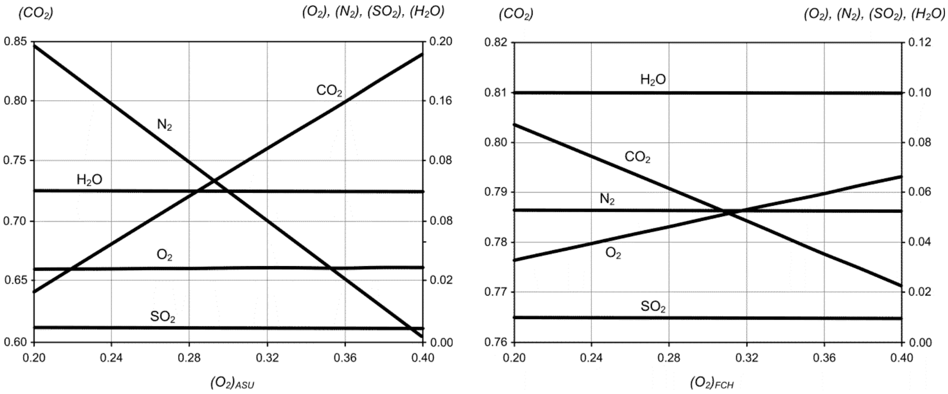

Figure 7: Composition of exhaust gas at the outlet from flue gas dryer as a function of oxygen content in oxidant: a) in FCH, b) in ASU.

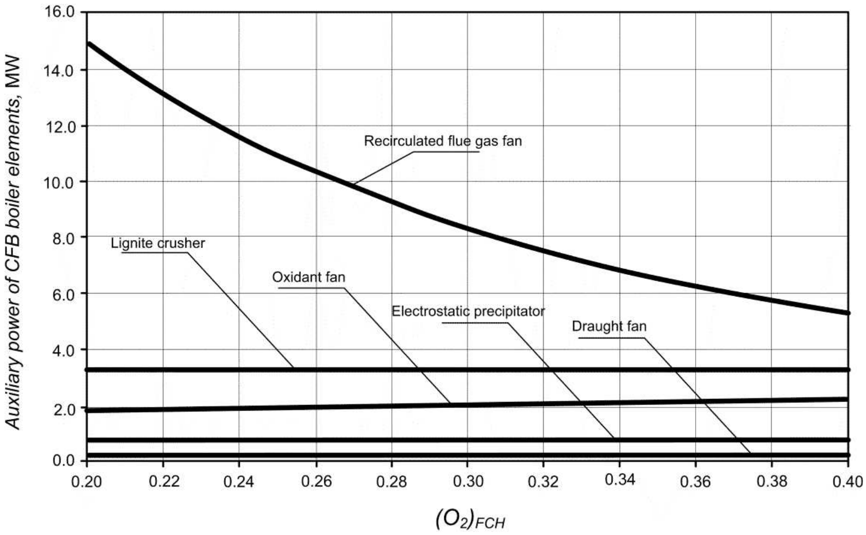

Figure 8: Auxiliary power of CFB boiler elements as a function of oxygen content in oxidant.

supplied to the furnace chamber the mass flow of recalculated flue gases significantly decreases. Consequently, a decrease of auxiliary power of recirculated flue gases fan (F2, see Fig. 1) is observed. The auxiliary power of exhaust gas fan due to the low pressure difference is insignificant and does not exceed 200 kW. Also, the auxiliary power of the electrostatic precipitator is on the marginal level, and does not exceed 700 kW. The change of oxygen share in the oxidant supplied to the furnace chamber insignificantly influence the change of lignite crusher auxiliary power. The increase of this oxygen share causes the slight increase of auxiliary power of the oxidant fan.

5 Summary

One of the key benefits of using oxy-combustion technology is a significantly reduced amount of exhaust gases emitted from the installation in comparison to traditional coal-fired boilers with comparable power. In addition, in the flue gas, carbon dioxide is a dominant component (above 80%), which in the perspective of integration with the installations of CO_2 capture and preparation for transport (CCS) will greatly facilitate the process of separating the carbon dioxide from the exhaust gas.

Developed computational model of a CFB boiler will be used as a basis for building an integrated power system based on oxy-combustion technology. The simplicity of CFB boiler model allows for easy integration with any proposed technology of oxygen production including:

- cryogenic separation,
- high-temperature membranes,
- hybrid combination of cryogenic separation and low-temperature membranes.

Planned optimizations [16,17] will allow to select the best solutions of integration of the various installations included in the integrated oxy system.

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