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Modeling of a supercritical power plant with an oxy type pulverized fuel boiler, a carbon dioxide capture unit and a 'four-end' type membrane air separator

The analysis of a 600 MW supercritical power plant with parameters of life steam at 30 MPa/ /650 °C and of reheated steam 6 MPa/670 °C was made. Power plant is equipped with the following units: oxy type pulverized fuel boiler, 'four-end' high temperature membrane air separator and carbon dioxide capture system which were modeled. With the assumption of a constant gross power of the analyzed power plant, the thermal efficiency of the boiler and the steam cycle efficiency were calculated. These parameters were designated as a function of the recovery rate of oxygen in the air separation unit. This allowed to determine gross and net efficiency of electricity generation.

1 Introduction

Currently observed in the world trend in efforts to reduce emissions, especially of greenhouse gases, contributes to significant changes in the direction of the development of energy technologies [1–2]. Such a gas emitted in large quantities by industry and power plants, is carbon dioxide. To minimize emission of this gas the energy sector is working currently on the optimization of a power plant, both in the area of its structure, as well as in the area of operation parameters [3] and on the technology of zero emission coal power plants. Currently three directions of carbon capture technologies in order to minimize energy consumptions are developed:

- pre-combustion technology,

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- post-combustion technology,
- oxy-combustion technology.

In the area of coal technologies all of these solutions can be used. The use of post-combustion technologies for existing power plants is described in [4–5] and for new ones is described in [6–9]. Among new coal fired power plants large hopes are associated with oxy-combustion technology, of which the principal purpose is combustion of coal in the oxygen-rich atmosphere in order to eliminate the nitrogen from the exhaust gases. Currently in the research area of oxy-combustion technology, the solutions aiming for decreasing the energy consumption connected with oxygen production in the air separation unit are searched for [10–14].

The gross electric power of power plant analyzed in these paper is equal to 600 MW. The parameters of life steam are at 30 MPa/650 °C and of the reheated steam 6 MPa/670 °C. This power plant is equipped with steam cycle for supercritical parameters, oxy type pulverized fuel boiler, 'four-end' type high temperature membrane air separator and carbon dioxide capture unit.

2 Modeling of system components

A model of the analyzed power plant contains integrated models of steam cycle, oxy type pulverized fuel boiler, air separation unit and carbon dioxide capture unit. The influence of a change of the oxygen recovery rate of an air separation unit on a work of the entire power plant was analyzed. Assumption of constant gross electric power of steam turbine and thermodynamic parameters of life and reheated steam in steam cycle was made, meaning that the thermodynamic parameters and mass flow rates in steam cycle remained constant, despite the change of oxygen recovery rate. Therefore, calculation of the steam cycle model were carried out once and then the value of reheated steam temperature at the inlet to boiler, mass flow rates of life and reheated steam were transferred to a boiler model. The models of oxy-type pulverized fuel boiler and air separation unit were connected in one model shown in Fig. 2, made in GateCycle software due to strong interaction between them. The model of carbon dioxide capture unit collects the information about mass flow rate, temperature, pressure and composition of flue gas from boiler model.

The steam cycle consists of a boiler with reheated steam (B), steam turbine consisting of high-pressure part (HP), intermediate-pressure part (IP) and low-pressure part (LP), electricity generator (G), condenser (CND), deaerator (DEA), condensate pump (CP), feed water pump (MP), extraction condensate

pumps (ECP), seven regenerative heat exchangers four low-pressure (FWH1–4) and three high-pressure (FWH5–7)) and steam cooler (SC). The low-pressure regenerative heat exchangers are fed from the bleedings of intermediate- and low-pressure part, while the high-pressure regenerative heat exchangers are feed from the extractions of high- and intermediate-pressure part of the steam turbine. The structure of steam cycle is shown in Fig. 1.

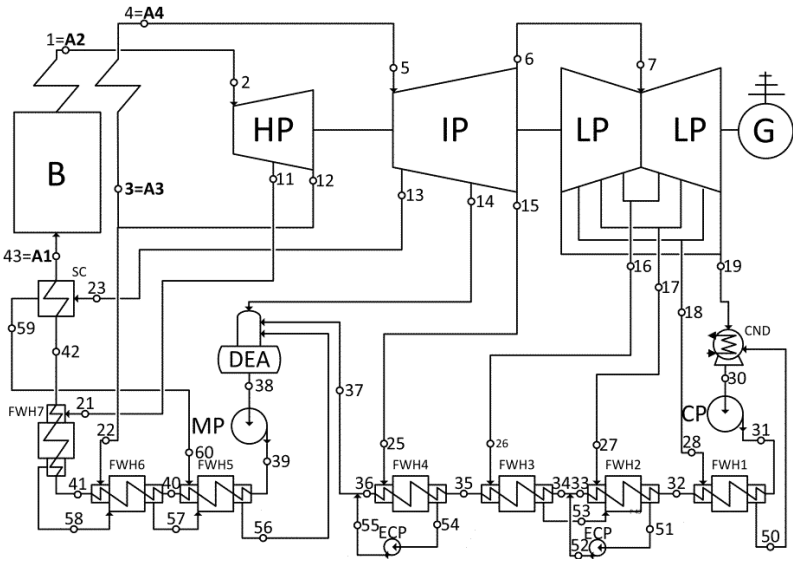

Figure 1. Scheme of steam cycle.

Air separation unit (ASU) structure consists of: a counter-current air heater (APH), an air compressor (C), an expander (EX), a generator (G) and a 'four-end' type membrane (M). The expander like in classic gas turbine units, drives the air compressor. Depending on the assumed quantities the expander and compressor can give or take electricity from the grid. Oxy-type pulverized fuel boiler structure consist of: a combustion chamber (CC), an evaporator divided into two parts (EVAP), a counter-current air heater (APH), two recirculated flue gas heaters (RHX1 and RHX2), a live steam superheater (LSSH), a reheated steam superheater (RSSH), an economizer (ECO), an electrostatic precipitator (EP), a flue gas extractor fan (F1), a flue gas dryer (FGD) and a recirculated flue gas fan (F2). The structure of air separation unit integrated with the oxy type pulverized boiler is shown in Fig. 2. The recirculated flue gas are retrieved before flue gas dryer, so this gas have high moisture content. The basic characteristic quantities of integrated models are gathered in Tab. 1.

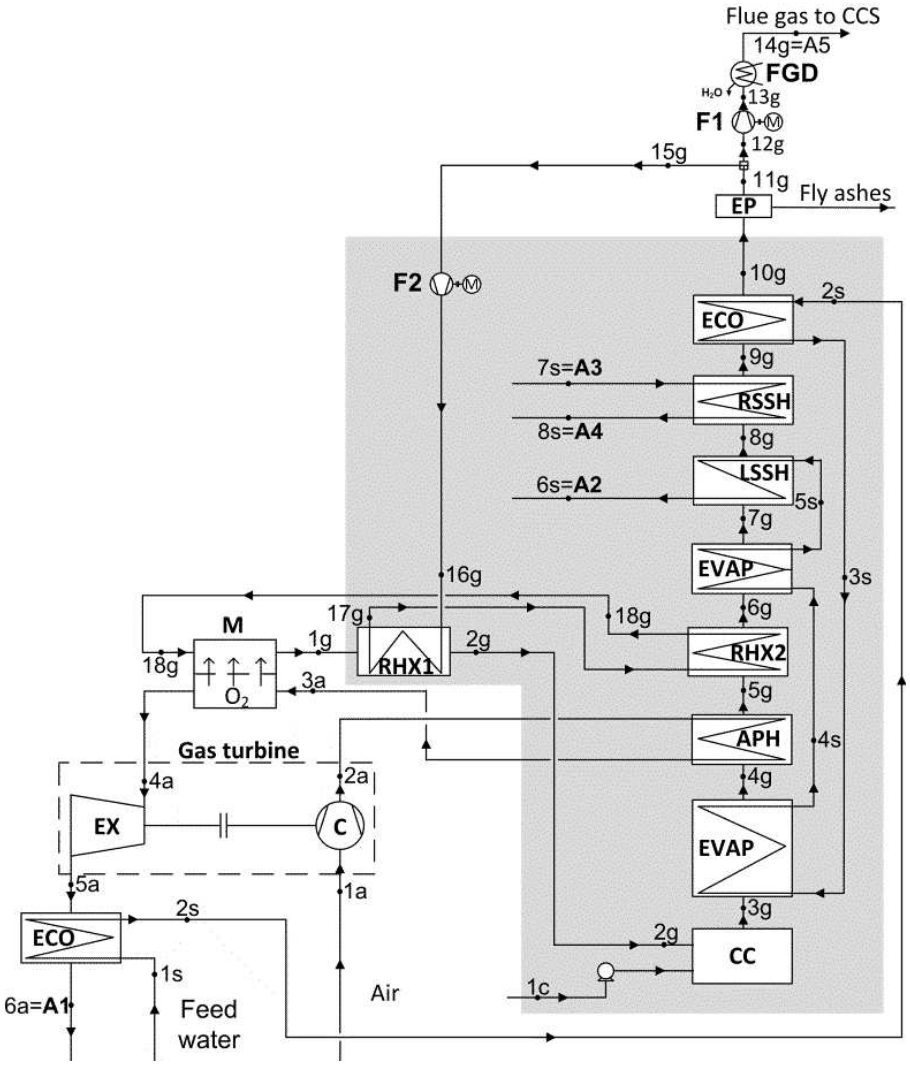

Figure 2. Scheme of the air separation unit (ASU) integrated with oxy-type pulverized boiler.

Energy consumption of the carbon dioxide capture unit (CCS) was calculated with the use of the model of carbon dioxide capture unit. The structure of this model is shown in Fig. 3. The energy consumption value is correct only for analyzed power plant and more precisely for the specific composition of the flue gas. Points connecting the various models shown in Figs. 1, 2 and 3 are marked as A1, A2, A3, A4 and A5 on these figures. Analysis of methods for reduction of

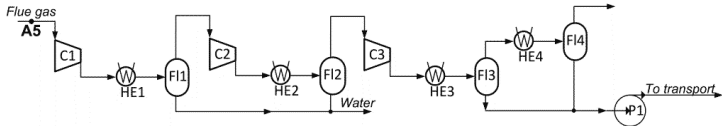

Figure 3. Scheme of the carbon dioxide capture unit (CCS).

energy consumption of carbon dioxide capture units are described in [15]. It was assumed that pressure at the outlet of three compressors C1, C2 and C3 in carbon dioxide capture unit is equal to 0.6 MPa, 2.5 MPa and 3.0 MPa. The pressure of carbon dioxide at the outlet of carbon dioxide pump is equal to 15 MPa. In part of carbon dioxide capture unit where the flue gas is dried, the temperature of gas at the outlet of HE1 and HE2 heaters is equal to 30 °C. In the second part of these unit, the temperature of gas flowing out from HE3 heater is equal to -20 °C and from HE4 heater is equal to -55 °C. The analysis of this installation showed, that 0.927 kg of carbon dioxide with a purity of 96.4% is separated from 1 kg of flue gas flowing into CCS unit.

3 Calculation methodology

The boiler thermal efficiency depends on the live steam flow rate ($\dot{m}_{LS}$), the reheated steam flow rate ($\dot{m}_{RS}$), the enthalpy of live steam leaving the boiler (h_{LS_out}), the enthalpy of feed water at the inlet to the boiler (h_{FW_in}), the enthalpies of reheated steam leaving the boiler (h_{RS_out}), and at the inlet to the boiler (h_{RS_in}), respectively the fuel mass flow rate ($\dot{m}_C$) and fuel lower heating value (W_{lh}).

$$\eta_k = \frac{\dot{m}_{LS}\left(h_{LS_out} - h_{FW_in}\right) + \dot{m}_{RS}\left(h_{RS_out} - h_{RS_in}\right)}{\dot{m}_C W_{lh}} \,. \tag{1}$$

The gross efficiency of electricity generation is calculated in terms of the generator electrical power driven by the steam turbine. The electricity generated in other units is included in their auxiliary recovery rates. The gross efficiency of electricity generation depends on the steam turbine electrical power (N_{el}), the fuel flow rate ($\dot{m}_C$) and lower heating value (W_{lh})

$$\eta_{el,gross} = \frac{N_{el}}{m_{1c} W_{lh}} \,. \tag{2}$$

The net efficiency of electricity generation depends on the gross efficiency of electricity generation ($\eta_{el,gross}$), the auxiliary power rate of air separation unit

($\delta_{apr,ASU}$), the auxiliary power rate of carbon dioxide capture unit ($\delta_{apr,CCS}$), the auxiliary power rate of steam cycle ($\delta_{apr,SC}$) and the auxiliary power rate of the boiler ($\delta_{apr,B}$)

$$\eta_{el,net} = \eta_{el,gross}(1 - \delta_{apr,ASU} - \delta_{apr,CCS} - \delta_{apr,SC} - \delta_{apr,B}) \ . \tag{3}$$

The auxiliary power rate of the air separation unit depends on the mechanical power used to drive the compressor (N_{eC}), the mechanical power generated in expander (N_{eEX}), the steam turbine electric power (N_{el}) and the generator efficiency (η_g)

$$\delta_{apr,ASU} = \frac{-\left(N_{eEX} - N_{eC}\right)\eta_g}{N_{el}} \ . \tag{4}$$

Auxiliary power rate of carbon dioxide capture unit depends on power of three parts of compressor (ΣN_{C1-3}),power of carbon dioxide pump (N_{P1}) and the steam turbine electrical power (N_{el})

$$\delta_{apr,CCS} = (\Sigma N_{C1-3} + N_{P1})/N_{el} \ . \tag{5}$$

Auxiliary power rate of steam cycle depends on power of a condensate pump (N_{CP}), power of a main cycle pump (N_{MP}), power of extraction condensate pumps (ΣN_{ECP}) and the steam turbine electrical power (N_{el})

$$\delta_{apr,SC} = (N_{CP} + N_{MP} + \Sigma N_{ECP})/N_{el} \ . \tag{6}$$

Auxiliary power rate of the boiler depends on power of a flue gas fan (N_{F1}), power of a recirculated flue gas fan (N_{F2}), power of a coal mill (N_{CM}), power supplied to an electrostatic precipitator (N_{EP}) and the steam turbine electrical power (N_{el})

$$\delta_{pw,K} = (N_{W1} + N_{W2} + N_{MW} + N_{EF})/N_{el} \ . \tag{7}$$

4 Assumptions and results of calculation

The steam cycle is supplied with life steam at 654.9 °C/31.1 MPa and with reheated steam at 672.4 °C/6.0 MPa. The gross electric power of steam turbine is constant and is equal to 600 MW. Temperature of feed water at the inlet to boiler is equal to 310 °C. Temperature of reheated steam at the inlet to boiler, mass flow rate of life steam and reheated steam is calculated with steam cycle model. Next, these values are transferred to the model of oxy type pulverized fuel boiler. The basic characteristic quantities of a boiler model integrated with air separation unit and carbon dioxide capture unit models are gathered in Tab. 1.

Table 1. Characteristics quantities for considered air separation unit integrated with the oxy type pulverized fuel boiler

Name	Symbol	Value	Unit
Excess air coefficient	λ	1.2	–
Increase of water temperature in two economizers	Δt_{ECO}	43	K
Specific temperature difference of the economizer	$t_{10g} - t_{2s}$	55	K
Steam temperature between evaporator and superheater	t_{5s}	480	^{o}C
Efficiency of heat exchangers in the boiler	η_{wck}	99.8	%
Moisture content in the dried flue gas	$(H_2O)_{14g}$	10	%
Share of oxygen in the mixture of the flue gas and oxygen from ASU supplied to the combustion chamber	$x_{O2,per}$	0.3	$\frac{\text{kmol,O}_2}{\text{kmol,gw}}$
Flue gas pressure directed to CC	p_{14g}	101.32	kPa
Share of slag in the ash / Share of fly ash in the ash	u/u_{pl}	40/60	%
Share of carbon element from coal in the ash	c	0.5	%
Membrane work temperature, Temperature of flue gas at the inlet to the separation membrane	$t_{mem}; t_{18g}$	850	^{o}C
Specific temperature difference of the permeate-recycled flue gas heat exchanger	$\Delta T_{sP-S} = = t_{1g} - t_{17g}$	50	K
Compressor pressure ratio	β_k	15	–
Energy consumption of electrostatic precipitator		1	kJ/(kg,FG)
Energy consumption of hard coal mill		43.6	kJ/(kg,HC)
Energy consumption of carbon dioxide capture unit		316.03	kJ/(kg,FG)

Composition of hard coal supplied to power plant is as follows: carbon – 61.25%, sulfur – 1.10%, hydrogen – 3.9%, nitrogen – 0.25%, oxygen – 6.5%, water – 17.32%, ash 9.00%. The fuel lower heating value is equal to 24078 kJ/kg. It was assumed that the air taken from environment is a dry gas consisting of 21% oxygen and 79% nitrogen (volumetric composition). The ambient temperature and pressure is equal to 20 ^{o}C and 101.3 kPa respectively. The oxygen recovery rate of the air separation unit was changed during analysis, in the range from 55% to 100% with 1p.p. step. It was assumed that gas permeating through separation membrane contains only oxygen.

Figure 4 shows a graph of boiler thermal efficiency as a function of oxygen recovery rate of the air separation unit. It should be noted that the boiler thermal efficiency increases from about 68% for low oxygen recovery rates to about 83% for high recovery rates. Figure 5 shows a graph of auxiliary power rates of the boiler, steam cycle and carbon dioxide capture unit as a function of oxygen recovery rate. Figure 4 shows a graph of the auxiliary power rate of the air separation unit. It should be noted that the auxiliary power rate of the air separation unit, unlike the other auxiliary power rates, has a negative value in

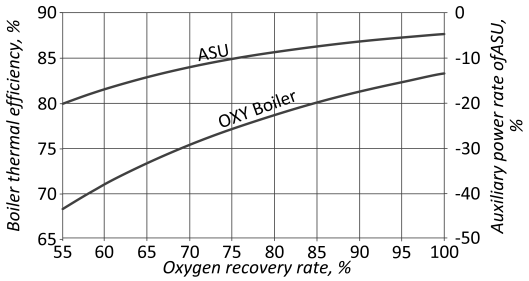

Figure 4. Thermal efficiency of the oxy type boiler and the auxiliary power rate of the air separation unit as a function of the oxygen recovery rate.

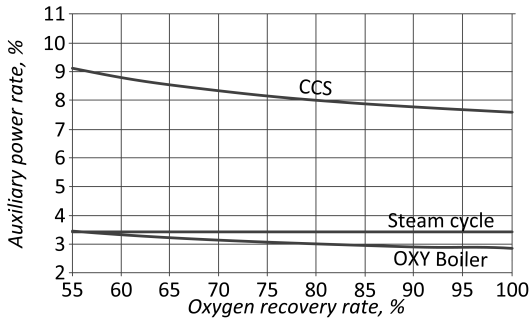

Figure 5. The auxiliary power rates of carbon dioxide capture unit (CCS), boiler and steam cycle as a function of the oxygen recovery rate.

the studied range of oxygen recovery rates. The reason is that the expander in the air separation unit produce more power than is needed to drive the air compressor. Figure 6 shows a graph of the gross and net efficiency of electricity generation as a function of oxygen recovery rate. This characteristics were determined with the use of Eqs. (2) and (3).

5 Summary

In this paper the oxy type pulverized boiler integrated with 'four-end' high temperature membrane air separator, steam cycle and carbon dioxide capture unit was analyzed. The oxy type boiler supplies the live steam and the reheated steam to the steam cycle. The gross power of the steam cycle generator is equal to 600 MW. For the analysis the characteristics of the boiler thermal efficiency unit as a function of oxygen recovery rate in the air separation unit were determined. Also, auxiliary power rate of the steam cycle, carbon dioxide capture unit and air

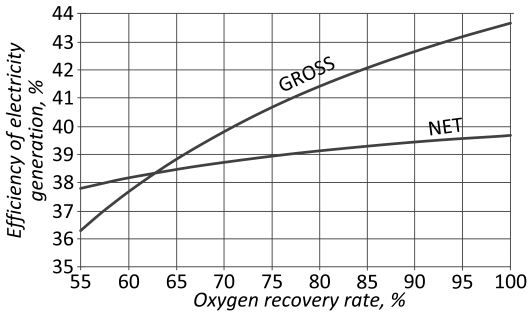

Figure 6. Gross and net efficiency of electricity generation as a function of the oxygen recovery rate.

separation unit as a function of the same recovery rate were determined. Mentioned efficiency and auxiliary power rates must be considered together, because they determines the electricity generation efficiency of analyzed power plant.

The auxiliary power rate of the carbon dioxide capture unit and the auxiliary power rate of the oxy type pulverized boiler decreases with increasing the oxygen recovery rate. The auxiliary power rate of the steam cycle is the same for all oxygen recovery rates, because the power of steam turbine is held at a constant level. The auxiliary power rate of the air separation unit unlike the other auxiliary power rates has a negative value in the studied range. This means that the expander generates more power than the power needed to drive the compressor. Excess power from expander is used to generate electric power in generator. The additional power generated in the air separation unit decrease with increase of oxygen recovery rate. The value of the net efficiency of electricity generation for analyzed power plant is increasing from about 37.8% to about 39.7%. This characteristic is nonlinear. The studied integrated models have the highest net overall efficiency for the oxygen recovery rate equal to 100%.

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Modelowanie elektrowni na parametry nadkrytyczne z kotłem pyłowym typu oxy, instalacją cc oraz membranowym separatorem powietrza typu '*four-end*'

S t r e s z c z e n i e

W artykule analizowano elektrownie o mocy 600 MW i parametrach pary świeżej 30 MPa/650 °C i wtórnej 6 MPa/670 °C. Elektrownia wyposażona jest w następujące instalacje: kocioł pyłowy typu oxy, wysokotemperaturową membranę do separacji powietrza typu '*four-end*' oraz instalację przygotowania i sprężania CO_2. Wymienione instalacje zostały zamodelowane. Przy założeniu stałej mocy brutto analizowanej elektrowni wyznaczono zapotrzebowanie na moc zamodelowanych instalacjach, sprawność obiegu parowego oraz sprawność termiczną kotła. Wielkości te wyznaczono w funkcji stopnia odzysku tlenu w membranie. Pozwoliło to wyznaczyć sprawność wytwarzania energii elektrycznej netto.

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