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Supercritical power plant 600 MW with cryogenic oxygen plant and CCS installation

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Abstract This article describes a thermodynamic analysis of an oxy type power plant. The analyzed power plant consists of: 1) steam turbine for supercritical steam parameters of 600 °C/29 MPa with a capacity of 600 MW; 2) circulating fluidized bed boiler, in which brown coal with high moisture content (42.5%) is burned in the atmosphere enriched in oxygen; 3) air separation unit (ASU); 4) CO_2 capture installation, where flue gases obtained in the combustion process are compressed to the pressure of 150 MPa. The circulated fluidized bed (CFB) boiler is integrated with a fuel dryer and a cryogenic air separation unit. Waste nitrogen from ASU is heated in the boiler, and then is used as a coal drying medium. In this study, the thermal efficiency of the boiler, steam cycle thermal efficiency and power demand were determined. These quantities made possible to determine the net efficiency of the test power plant.

Keywords: CFB oxy boiler; Oxy-combustion system; Supercritical oxy power plant; Electricity generation efficiency; Cryogenic air separation

Nomenclature

$EN_{ASU,KRIO}$ – energy consumption of the cryogenic air separation unit, kWh/kg O_2
EN_{CCS} – energy consumption of CO_2 separation installation, kWh/kg CO_2
h – enthalpy, kJ/kg
$\dot{m}$ – mass flow rate, kg/s

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$(\dot{m}_{CO_2})_{1dw}$ – mass flow rate of carbon dioxide at the outlet of CCS installation, kg/s
$(\dot{m}_{O_2})_{4o}$ – mass flow rate of oxygen at the outlet of air separation unit, kg/s
$\dot{m}_{1c}$ – fuel mass flow rate at the inlet of CFB boiler, kg/s
N_C – electric power of flue gas compressor, MW
$N_{el,ASUKRIO}$ – auxiliary power of cryogenic air separation unit, MW
$N_{el,CCS}$ – auxiliary power of CCS installation, MW
$N_{el,CFB}$ – auxiliary power of CFB boiler, MW
$N_{el,CP}$ – electric power of condensate pump, MW
$N_{el,FWP}$ – electric power of feed water pump, MW
$N_{el,g}$ – gross power of power plant, MW
$N_{el,PW}$ – total auxiliary power of power plant, MW
$N_{el,ST}$ – auxiliary power of steam turbine, MW
N_P – electric power of pump of liquid CO_2, MW
N_{SP} – electric power of air compressor, MW
p – pressure, Pa
t – temperature, K (°C)
$\dot{Q}_{uz}$ – heat supplied to steam cycle, MW
W_d – lower heating value of fuel, kJ/kg

Greek symbols

$\delta_{ASU,KRIO}$ – auxiliary power rate of cryogenic air separation unit
δ_{CCS} – auxiliary power rate of CO_2 separation installation
δ_{CFB} – auxiliary power rate of CFB boiler
δ_{PW} – total auxiliary power rate of power plant
δ_{ST} – auxiliary power rate of steam turbine
$\eta_{el,netto}$ – net efficiency of electricity generation
$\eta_{t,ST}$ – thermal efficiency of steam turbine
η_{tk} – thermal efficiency of CFB boiler

1 Introduction

Currently, power industry still relies mainly on burning fossil fuels such as: coal, lignite, petroleum and natural gas. In Poland, production of electricity using coal and natural gas, is exceeding 90% [1]. Combustion of fossil fuels produces large quantities of carbon dioxide (CO_2), introduced directly into the atmosphere, which is the main component of greenhouse gases, next to SO_2 and NO_x. One of the most harmful of chemical compound is CO_2, which is formed as a result of human activity, mainly. As many as 34% of global greenhouse gas emission into the atmosphere comes from the combustion of coal [2]. To reduce this phenomenon, the European Union adopted the so-called climatic – energy directive: that put some important assumptions concerning the energy production that must be complied by

2020. In relation to the year 1990 these are:

- reduce of greenhouse gases emitted to atmosphereby 20%,
- reduce of primary energy consumption by 20%,
- increase of the share of renewable energy to 20% of total energy consumption in the European Union.

In order to achieve these requirements, several mechanisms to enhance the reduction of emissions have been introduced. These are:

- JI – ioint implementation,
- CDM – clean development mechanism,
- ET – emission trading,
- activation mechanism of CO2 absorption by plants.

In Poland, the legal basis for the implementation of European directives to meet the objectives of the Kyoto Protocol is *the Act of 22 December 2004, on emissions trading for greenhouse gases and other substances.* The purpose of its creation is 'to reduce emissions in a cost-effective and economically efficient manner'. It obliges the Ministry of Environment to issue a series of executive acts, establishing mechanisms of the system, and the most important of these is the National Allocation Plan, issued by the Council of Ministers [3]. In addition to the energy sector, in this plan were also included: refining industry, ceramic and glass industry, chemical industry, paper industry and coke industry. Its publication has become a reference moment to start emissions trading system in Poland.

Currently, power engineering is interested in the search for a so-called zero- or nearly zero-emission technology. Methods that contribute to the reduction of CO_2 emissions from power plants, include technologies such as separation of carbon dioxide before the combustion process (pre-combustion), CO_2 capture from flue gas (postcombustion) and burning of the fuel in oxygen atmosphere (oxy-combustion) [4].

The carbon dioxide capture technology before the combustion process, includes the processes of decarbonisation of fuel, i.e., the separation of elementary carbon from the gaseous fuel (where the main components are carbon dioxide and H_2), formed as the result of the conversion of coal, such as gasification. Carbon dioxide separation from flue gases may be used in the existing power plant units. The only additional component of the power plant is the system of separation of CO_2, which can used all known methods of separation, i.e. absorption, adsorption [5], membrane or cryogenic methods.

The main aim of the oxy-fuel combustion is increasing the CO_2 in flue gases. The concept of this technology is based on the combustion of fuel in the oxy-enriched atmosphere. In the case of use of oxygen instead of air, exhaust gases are not diluted with nitrogen, which results in a smaller volume of flue gas stream. The main components of the exhaust gas are CO_2 and H_2O, which greatly facilitates the separation of carbon dioxide from flue gases and reduces its emissions almost completely.

The combustion of fuel in pure oxygen results in a significant increase in exhaust gas temperature. This is due to the lack of the so-called nitric ballast, which absorbs the heat during the conventional combustion in the air. Due to the technical and constructional boiler aspects to lower the temperature in the combustion chamber, in the oxy-fuel combustion technology, the partial exhaust gas recirculation is used. In this way, in fact, combustion process takes place in the atmosphere of the mixture of high purity oxygen (over 95%) and gas rich in CO_2 and H_2O. Oxygen, which is required for oxy-combustion, is achieved in the air separation unit. Currently, only cryogenic air separation allow to obtain sufficient amount of oxygen for combustion in oxy-type plants (of the order of several thousand tones of O_2 per day).

An important advantage of the oxy-fuel combustion is the possibility of burning of low calorific fuels, with high moisture and ash content (such as lignite). The challenges posed to this technology before introducing it to power plants are: the development of an efficient and cheap method of obtaining oxygen, temperature control in the boiler furnace chamber and CO_2 sequestration.

The aim of this work is to determine the net efficiency of electricity generation of the analyzed oxy-type power plant, and the inluence of the energy consumption of the cryogenic air separation unit on that efficiency.

2 Description of the analyzed power plant

Figure 1 shows the structure of the analyzed oxy power plant. It is composed of subsystems such as: a steam turbine (ST), a circulated fluidized bed boiler (CFB), a cryogenic air separation unit (ASU KRIO) and an installation of carbon capture and storage (CCS).

The computational models of the components, of the analyzed oxy-type power plant, were developed within the commercial programes GateCycle [6]

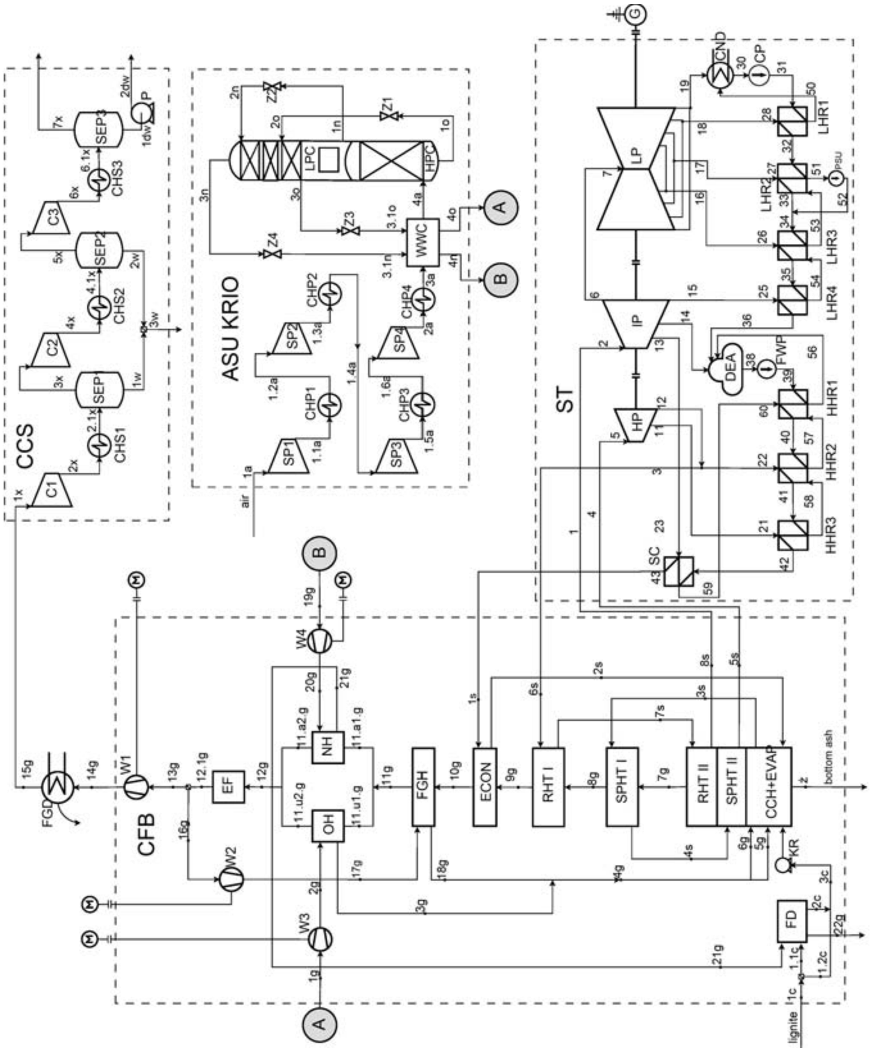

Figure 1. Scheme of the supercritical power plant working in oxy-fuel combustion technology (ST – steam turbine, HP – high pressure turbine, IP – intermediate pressure turbine, LP – low pressure turbine, CND – condenser, DEA – deaerator, FWP – feed water pump, CP – condensate pump, LHR – low pressure feed water heater, HHR – high pressure feed water heater, SC – steam cooler, G – generator; CFB – circulated bed boiler, CCH+EVAP – combustion chamber + evaporator, SPHT - superheater, RHT – reheater, ECON - economizer; FGH – flue gas heater; OH – oxygen heater, NH – nitrogen heater, EF – electrostatic precipitator, FGD – flue gas dryer, W – fan, FD – fuel dryer, KR – coal crusher; ASU KRIO - cryogenic air separation unit, SP – air compressor, CHP – air cooler, WWC - multi-streaming heat exchanger, HPC – high pressure distillation column, LPC – low pressure distillation column, Z – valve; CCS – CO_2 separation installation, C – flue gas compressor, SEP – moisture separator, CHS – flue gas cooler, P – liquid CO_2 pump).

(steam cycle, CFB boiler module) and Aspen Plus [7] (cryogenic air separation unit, CCS installation). To calculate the fuel dryer, the own code was used [8].

The steam turbine is the most important part of the steam cycle, in which assumed parameters of the live steam are 29 MPa and 600 °C, and parameters of the reheated steam at the turbine inlet: 5 MPa and 620 °C. Assumed deaerator pressure is equal to 1.2 MPa, condenser pressure to 5 kPa and condensate pump pressure to 1.6 MPa. Feed water temperature at the inlet to the boiler is assumed at 570.15 K. Gross power of the power plant, produced by the generator, is 600 MW, and the efficiency of the generator is equal to 0.99.

In the regeneration system of steam turbine there are seven regenerative heat exchangers (four low-pressure (LPC) and three high-pressure (HPC)) and a steam cooler. Other information necessary for the calculation of the steam turbine system are described in detail in [9] and these are shown in Tab. 1.

Table 1. Assumptions for the calculation of the steam turbine.

Quantities	Values	Unit
Isentropic efficiency of groups of stages of high-pressure, intermediate-pressure and low-pressure steam turbine	90; 93; 86	%
Isentropic efficiency of the least group of stages of low-pressure steam turbine	81	%
Isentropic efficiency of pumps	85	%
Efficiency of regenerative heat exchangers, steam cooler and deaerator	99.5	%
Steam turbine mechanical losses	4.6	MW
Pressure drop of water flowing through the regenerative heat exchangers and steam cooler	6; 0.5	%
Pressure drop of steam in steam reheater, and steam in reheated steam pipelines	1.4; 2.4	%
Pressure drop between intermediate- and low-pressure part of steam turbine	0.5	%

All assumed values allow to determine the live steam flow (431.02 kg/s) and the reheated steam flow (364.82 kg/s), and heat supplied to the steam cycle (1181.7 MW).

The CFB boiler is fed with lignite, of which parameters were assumed based on the characteristics delivered from the coal mine Turów. Lower heating value is equal to 9960 kJ/kg and the mass composition is: carbon –

0.286, sulfur – 0.0095, hydrogen – 0.022, nitrogen – 0.0025, oxygen – 0.08, ash – 0.1754, moisture – 0.425. In this system wet flue gases recirculation was assumed, which is more advantageous in terms of thermal efficiency of the boiler in relation to the dry flue gas recirculation [10].

The task of the boiler is to provide live steam and reheated steam flow rates with specified parameters. Parameters of the live steam and reheated steam at the output of steam turbine are respectively: 30.1 MPa/ 604.9 °C, and 5.12 MPa/622.4 °C. It was assumed that the boiler feed water delivered in the amount of 431.02 kg/s, has a temperature equal to 570.15 K. In addition, values of temperature of the media at the outlets of the water heater (ECON) and evaporator (EVAP), were assumed, respectively, at 613.15 K and 753.15 K. The temperature difference at the 'hot end' of the economizer is 55 K. Oxidant mixture contains 30% of oxygen, and the remainder part of the oxidant is recirculated flue gas. The ratio of excess oxidant is 1.2. The boiler is integrated into the fuel dryer, in which the nitrogen is a drying medium of coal (nitrogen is a byproduct of the air separation process). It was also assumed that the temperature differences at the 'cold ends' of the recirculated flue gas heater is 23 K, and 30 K in the oxygen heater and the nitrogen heater.

A relative heat loss by radiation in the boiler was assumed at 0.2%, and the unburned carbon content in the fly ash and in the bottom ash at 0.5%. The ratio of bottom ash to fly ash is 40% / 60%. The efficiency of fans within the boiler was assumed at 0.75. The air at the composition of O_2 0.21/$N_2$0.79 and at ambient parameters (assumed as 288.15 K and 0.1013 MPa) is supplied to the cryogenic air separation unit, where it is compressed in a multistage air compressor to the pressure of 0.6 MPa, and intercooled to the temperature of 293.15 K.

Isentropic efficiency and mechanical efficiency of the air compressor were assumed equal to 0.85 and 0.99, respectively, and power losses in the machine assumed at 1%. Next, the air stream flows through the multistreaming heat exchanger, where is partially condensed and cooled to the temperature, which is required to the cryogenic air separation process. The air separation unit (ASU KRIO) structure in the system under study is based on a Linde's double column, where oxygen of purity up to 99.8% is possible to be obtained [11].

In both, high- and low- pressure distillation columns (HPC and LPC, respectively) the number of distillation stages was assumed 50 in each of them, and the assumed profiles of pressure: 0.56–0.58 MPa in the HPC column, and 0.125–0.195 MPa in a LPC column. Pressure values for the different valves in the system was assumed in such a way, that the pressure of oxygen and nitrogen streams at the outlet of ASU KRIO was 0.1015 MPa. The oxygen purity at the outlet of the air separation unit is 99.5 vol.%. Quantity of oxygen stream is determined by the combustion conditions in the CFB boiler, and amounts to 119.80 kg/s. Assuming that the rate of oxygen recovery from air is equal to 1, the amount of air stream at the inlet to ASU KRIO is determined.

The flue gas stream leaving the CFB boiler, and is predryed in the flue gas dryer to a water content equal to 10%. In that way prepared exhaust gases (consisting mainly of CO_2 and H_2O) are directed to the CCS installation. In this system, the flue gas stream is compressed to the required pressure of 6.5 MPa. The temperature of intercooling is assumed equal to 319.22 K (the same as at the inlet to the CCS installation). The outlet, pressure from the subsequent compressors were assumed from the condition of equal pressure ratio in each of them.

The first two compressors together with moisture separators form a gas drying system. This system reduces flue gas stream moisture from 10 to 0.03%. Isentropic efficiency and mechanical efficiency of flue gas compressors, are assumed equal to 0.85 and 0.99, respectively. The compressor power losses is 1%, and the internal efficiency of the pump of liquid carbon dioxide is equal to 0.75. Pressure of the compressed CO_2 at the outlet of the pump was assumed at 15 MPa. In the CCS installation the recovery rate of CO_2 at the level of 90% was assumed. This quantity makes it possible to determine the temperature and the purity of the produced stream.

3 Algorithm and the results of the thermodynamic calculations

During of the calculations of the analyzed power plant, the values of the energy indicators of the power plant, such as the thermal efficiency of the boiler, auxiliary power of the system, and the net efficiency of electricity generation were determined.

The net efficiency of electricity generation in the system under study is described by the formula:

$$\eta_{el,netto} = \frac{N_{el,g} - N_{el,PW}}{\dot{m}_{1c} W_d} \ . \tag{1}$$

Equation (1) can be converted to:

$$\eta_{el,netto} = \frac{N_{el,g}(1 - \frac{N_{el,PW}}{N_{el,g}})}{\dot{m}_{1c} W_d} \ . \tag{2}$$

Using formulas of the thermal efficiencies of CFB boiler and the steam cycle, presented in the form of (3) and (4)

$$\eta_{tk} = \frac{\dot{Q}_{uz}}{\dot{m}_{1c} W_d} \ , \tag{3}$$

$$\eta_{t,ST} = \frac{N_{el,g}}{\dot{Q}_{uz}} \ , \tag{4}$$

the Eq. (2) can be written as

$$\eta_{el,netto} = \eta_{t,ST}\eta_{tk}\big(1 - \frac{N_{el,PW}}{N_{el,g}}\big) \ , \tag{5}$$

wherein, the auxiliary power is treated as

$$N_{el,PW} = N_{el,ST} + N_{el,CFB} + N_{el,ASUKRIO} + N_{el,CCS} \ . \tag{6}$$

In the Eq. (5), the element $\frac{N_{el,PW}}{N_{el,g}}$, can be substituted with the auxiliary power rate δ. Thus, it can also be written as

$$\delta_{PW} = \delta_{ST} + \delta_{CFB} + \delta_{ASU,KRIO} + \delta_{CCS} \ . \tag{7}$$

The auxiliary power of the steam turbine system depends mainly on the electric power required to drive a condensate pump and a feed water pump, what is describe as

$$N_{el,ST} = N_{el,CP} + N_{el,FWP} \ , \tag{8}$$

where: $N_{el,CP}$ - condensate pump electric power, MW; $N_{el,FWP}$ – feed water pump electric power, MW.

In the CFB boiler there are four fans: fan of exhaust gases, fan of recirculated part of flue gas, fan of high purity oxygen, and fan of nitrogen used in the system as a fuel drying medium. The auxiliary power of the CFB boiler depends on electric requirements of those fans, mainly. But we have to add the electric power required for the devices like coal crusher and flue gas electrostatic precipitator. To calculate their electric power, the energy consumption of these devices was assumed as: 5 kWh/Mg of lignite and 0.35 kWh/Mg of flue gas. The auxiliary power of the CFB boiler can be written as

$$N_{el,CFB} = N_{el,W1} + N_{el,W2} + N_{el,W3} + N_{el,W4} + N_{el,KR} + N_{el,EF} \ . \tag{9}$$

In the cryogenic air separation unit *ASU KRIO*, the auxiliary power is equal to the power required by a multisection air compressor, as follow:

$$N_{el,ASUKRIO} = \sum_{i} N_{el,SP_i} \ , \ (i - \text{number of section in air compressor}) \ . \tag{10}$$

Carbon dioxide capture from flue gas installation required electric energy for driving the flue gas compressors and the liquid high purity carbon dioxide pump. Quantity of this electric power is described as

$$N_{el,CCS} = \sum_{j} N_{Cj} + N_P \ , (j - \text{number of flue gas compressor}) \ . \tag{11}$$

The assumptions presented in Sec. 2 makes it possible to determine the thermodynamic parameters in each point of the analyzed oxy system. In the Tab. 2 values of mass flows of steam, water, flue gas, oxygen and nitrogen, as well values of temperature and pressure at each point of the CFB boiler are presented. Parameters of streams in the air separation unit and the CO_2 separation unit, are gathered in Tab. 3. Using parameters determined for each point in the system, we can determine all the components of Eq. (5), and ultimately, the net efficiency of electricity generation in the system under study.

The energy consumption of the cryogenic air separation unit can be determined using the formula

$$EN_{ASU,KRIO} = \frac{N_{el,ASUKRIO}}{(\dot{m}_{O_2})_{4o}} \ . \tag{12}$$

The energy consumption of the carbon capture installation is determined similarly. The auxiliary power of the CCS installation refers to a stream of pure CO_2, which is contained in the stream of carbon dioxide at the outlet of the system. We can describe it as follows:

$$EN_{CCS} = \frac{N_{el,CCS}}{(\dot{m}_{CO_2})_{1dw}} \ . \tag{13}$$

Table 2. Thermodynamic parameters of streams in the CFB.

Point	$\dot{m}$, kg/s	t, °C	p, kPa	h, kJ/kg
Steam-water				
1s	431.0	297.0	33791.7	1310.8
2s	431.0	340.0	33284.9	1540.5
3s	431.0	480.0	32119.9	2946.3
4s	431.0	579.9	30472.7	3372.9
5s	431.0	604.9	30074.3	3458.4
6s	364.8	333.6	5278.4	3015.4
7s	364.8	564.6	5151.3	3582.4
8s	364.8	622.4	5120.0	3717.3
Oxidant and flue gas				
1g	119.8	18.6	101.5	2.5
2g	119.8	35.5	118.0	18.1
3g	119.8	206.9	117.4	179.8
4g	413.4	301.4	117.4	338.0
5g	289.4	301.4	117.4	338.0
6g	124.0	301.4	117.4	338.0
7g	512.2	963.1	107.0	1378.0
8g	512.2	745.3	106.1	1023.7
9g	512.2	484.8	105.3	625.3
10g	512.2	351.9	103.8	434.7
11g	512.2	236.9	103.3	277.5
11.u1.g	110.6	236.9	103.3	277.5
11.u2.g	110.6	103.3	102.8	104.7
11.a1.g	401.6	236.9	103.3	277.5
11.a2.g	401.6	103.3	102.8	104.7
12g	512.2	103.3	102.8	104.7
12.1g	512.2	103.3	102.8	104.7
13g	218.6	103.3	102.8	104.7
14g	218.6	104.0	103.4	105.6
15g	152.3	46.1	101.3	26.5
16g	293.6	103.3	102.8	104.7
17g	293.6	119.2	118.0	124.5
18g	293.6	328.9	117.4	402.5
Nitrogen				
19g	392.9	18.6	101.5	2.921
20g	392.9	35.7	118.0	20.688
21g	392.9	206.9	117.4	199.735
22g	399.0	146.9	117.4	135.945
Lignite				
			Wd, kJ/kg	
1c	127.5	15.0	9959.7	-1.4
1.1c	34.4	15.0	9959.7	-1.4
1.2c	93.0	15.0	9959.7	-1.4
2c	28.3	126.9	12663.4	240.4
3c	121.3	38.1	10589.9	55.00

Table 3. Thermodynamic parameters of streams in ASU KRIO and CCS installations.

AIR SEPARATION UNIT				CCS INSTALLATION			
Point	$\dot{m}$, kg/s	p, kPa	t, °C	Point	$\dot{m}$, kg/s	p, kPa	t, °C
Air				Flue gas			
1a	512.75	1.013	15.00	1x	152.28	1.013	46.07
1.1a	512.75	1.580	60.80	2x	152.28	4.056	46.07
1.2a	512.75	1.580	20.00	2.1x	152.28	4.056	173.02
1.3a	512.75	2.465	66.58	3x	145.62	4.056	46.07
1.4a	512.75	2.465	20.00	4x	145.62	16.238	46.07
1.5a	512.75	3.846	66.60	4.1x	145.62	16.238	172.54
1.6a	512.75	3.846	20.00	5x	145.54	16.238	46.07
2a	512.75	6.000	66.63	6x	145.54	65.000	46.07
3a	512.75	6.000	20.00	6.1x	145.54	65.000	172.52
4a	512.75	5.900	-172.92	7x	19.87	65.000	5.89
Nitrogen							
1n	225.47	5.600	-177.56	Separated water			
2n	225.47	1.250	-193.83				
3n	392.94	1.250	-193.83	1w	6.66	4.056	46.07
3.1n	392.94	1.115	-194.12	2w	0.08	16.238	46.07
4n	392.94	1.015	18.59	3w	6.74	4.056	45.48
Oxygen							
1o	287.28	5.800	-173.14	Carbon dioxide			
2o	287.28	1.600	-188.08				
3o	119.80	1.950	-176.42				
3.1o	119.80	1.115	-177.86	1dw	125.68	65.000	5.89
4o	119.80	1.015	18.59	2dw	125.68	150.000	8.97
Pure O_2 stream at the outlet of ASU KRIO, $(\dot{m}_{O_2})_{4o}$, kg/s			119.28	Pure CO_2 stream at the outlet of CCS, $(\dot{m}_{CO_2})_{1dw}$, kg/s			119.61

Based on the previously discussed assumptions, in the calculations of the model of oxy power plant, the power consumption of the air separation unit was achieved at 0.226 kWh/kg O_2, and the energy consumption of the CCS was about 0.128 kWh/kg CO_2.

4 Summary

A reference power plant for the analyzed oxy-type power plant is the power plant with a power of 600 MW and the parameters presented in Sec. 2. A reference power plant is working in air combustion technology. The net efficiency of electricity production of power is equal to 42.51% [12]. Loss of efficiency of an oxy-type unit, with cryogenic air separation is therefore 10.26 percentage points, in relation to the reference power plant. The calculations indicate that a significant impact on the loss of the net power,

Table 4. Main energy indicators of oxy power plant with gross electric power 600 MW.

Quantities		Symbol		Unit		Values	
Boiler thermal efficiency		η_{tk}		%		93.09	
Steam turbine thermal efficiency		$\eta\ _{t,ST}$		%		50.78	
Auxiliary power of air separation unit	Auxiliary power rate of air separation unit	$N_{el,ASUKRIO}$	$\delta_{ASUKRIO}$	MW	–	97.1	0. 1618
Auxiliary power of CFB boiler	Auxiliary power rate of CFB boiler	$N_{el,CFB}$	δ_{CFB}	MW	–	18.3	0.0305
Auxiliary power of steam turbine	Auxiliary power rate of steam turbine	$N_{el,ST}$	δ_{TP}	MW	–	19.9	0.0332
Auxiliary power of CO_2 separation system	Auxiliary power rate of CO_2 separation system	$N_{el,CCS}$	δ_{CCS}	MW	–	55.2	0.0920
The total auxiliary power of power plant	The total auxiliary power rate of power plant	$N_{el,PW}$	δ_{PW}	MW	–	190.5	0.3178
Net efficiency of electricity		$\eta_{el,netto}$		%		32.26	

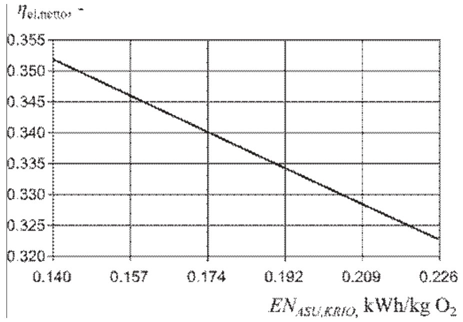

Figure 2. Net efficiency of the oxy-type power plant in relation to the energy consumption of a cryogenic air separation unit ASU KRIO.

has a cryogenic air separation unit, which requires the power at 97.1 MW, which corresponds to the unit energy requirement at 0.226 kWh/kg O_2.

Therefore, the increase of a power plant efficiency should be sought by reducing the energy consumption. Figure 2 shows, how the net efficiency of the analyzed power plant will increase, with decreasing the energy consumption of air separation unit to 0.14 kWh/kg O_2 while maintaining O_2

auxiliary power of other devices (except the cryogenic system) at the same level as in Tab. 4.

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