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Modelling and analysis of the carbon dioxide processing instalation using physical separation in a supercritical 460 MW coal unit working in oxy-combustion technology

The idea of oxy-combustion technology consists in burning fuel in the atmosphere of high purity oxygen. As a result, flue gas in such systems consists exclusively of almost carbon dioxide and water vapor. However, in practice, apart from CO_2 and H_2O, such compounds as argon, sulfur dioxide, nitrogen or oxygen appear in flue gas, which have to be separated to a great extent before CO_2 transport. The most frequently used method of the separation of these gases from the CO_2 stream is physical separation. In order to determine the energy intensity of the separation process, a numerical model of the carbon dioxide capture installation from the coal-powered unit operating in oxy-combustion system has been built in the Aspen Plus software. This paper presents the results of calculations of the energy intensity of the process, taking into account such parameters as purity and recovery rate of the separated CO_2 for a 460 MW supercritical unit. The analysis shows that reaching high purity and recovery rate of the carbon dioxide separated from flue gas is not difficult. However, reaching the required levels of other compounds content can be problematic. The main results are quantitatively presented in this paper. Some solutions for decreasing the energy intensity are also proposed.

1 Introduction

Limiting the emission of pollutants (including carbon dioxide) to the atmosphere has recently become an important element of the global energy policy. The largest amounts of pollutants arise from burning fuels, especially coal, in power generation systems. On the other hand, globally more than 40% of electricity

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is produced from coal [1], which seriously impedes limitation of the emissions esspecially eiven the increasing global energy demand. Such an intensive use of coal results mainly from its availability (almost equal distribution in the world) and relatively low price per heating value in comparison to other fuels. These advantages outweigh the disadvantages in the form of emissions of many pollutants, such as particulates, sulfur, nitrogen and carbon oxides or trace metals. Therefore, it should be expected that for many years coal will still dominate in the production of energy. On the other hand, the existing international agreements and laws (e.g. [2]) impose the need to reduce emissions of pollutants to the atmosphere, including carbon dioxide. This will cause the energy production with the use of coal to be much more expensive. The development of the flue gas cleaning technology resulted in a significant reduction of the emissions from coal power plants, which makes the reduction of CO_2 the most important of the current problems. Due to the fact that coal is responsible for 42% of anthropogenic emissions of this gas to the atmosphere [3], it has become a necessity to search for such solutions that will allow for significant reduction of the emissions. Measurable effects are brought by coal enrichment technologies, better organization of the combustion process, and, above all, the introduction of super- and ultra-supercritical steam parameters. However, emission-free operation of coal-fired units requires the introduction of carbon capture and storage (CCS) technology. The idea of this technology is to reduce carbon dioxide emissions through CO_2 capture, transport and long-term storage of this gas in an environmentally safe place. Carbon dioxide can be removed from the gas mixture before combustion (precombustion) after combustion (postcombustion) or by combustion in oxygen (oxy-fuel combustion). However, a significant drawback of each of these methods (despite their ensuring the required effect) is that they strongly reduce of the net efficiency of the system because of the need to bring large amounts of energy necessary to and compress the captured stream. They also cause an increase in the investment cost of power plants construction. Therefore, it is important to look for new methods to reduce energy consumption in the capture process through the use of new techniques and the integration of different installations within the entire system.

The main goal of this paper is to analyze the CO_2 capture installation in the oxy-fuel combustion systems. For this purpose, a numerical model of a gas processing (drying, cleaning and compression) installation in a coal power plant was built. The analyses were carried out primarily with the aim of determining the energy intensity of these systems and the possibility of its reduction.

2 Carbon dioxide processing in oxy-combustion systems

Oxy-fuel combustion (OFC) systems include, apart from the components typical for a coal-fired power plant, two additional plants. These are the installation for the separation of oxygen from air (air separation unit, ASU) that provide oxygen for the combustion process, as well as the one for the CO_2 capture, purification and compression (CPU – CO_2 compression and purification unit). An intervention in the boiler system, due to the changing conditions of the combustion process, is also necessary. Many different concepts of oxy systems can be found in the literature e.g., [4–8]. The choice will be based primarily on the results of optimization and economic analysis. A simplified diagram of the oxy-combustion system integrated with CO_2 capture is presented in Fig. 1.

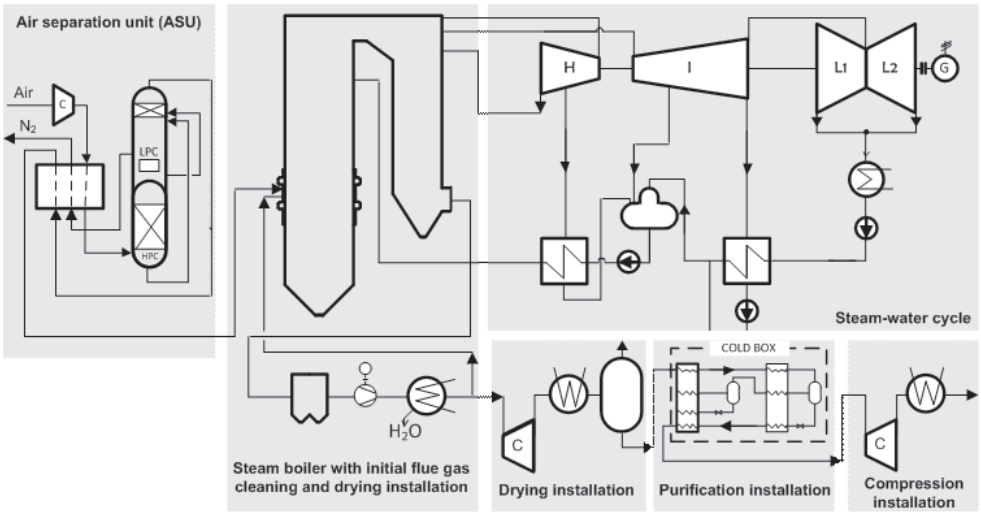

Figure 1. Diagram of the oxy-combustion system integrated with CO_2 capture.

The idea of the oxy-fuel combustion is to bring to the combustion process almost pure oxygen. The resulting flue gases consist mainly of carbon dioxide and water and therefore the preparation of CO_2 for transport to the storage place is theoretically relatively simple (it does not require the use of energy-intensive chemical methods). However, apart from CO_2 and H_2O, the flue gas contains also other gases, including in particular argon, nitrogen, oxygen and sulfur dioxide. Their presence is due, among others, to the excess of an oxidant in the combustion process; the presence of gases other than oxygen in the oxidant

from the air separation unit or leakages in the installation. The composition of gas in oxy systems also depends on the type of fuel or organization of the combustion process. Typical proportions of the particular gases in the flue gas from the oxy-combustion systems are as follows: argon 0–5%, nitrogen 0–15%, oxygen 0–7%, sulfur dioxide 0–1.5% [4].

Typically, the process of CO_2 separation in oxy-combustion systems consists of four main stages, i.e., flue gas stream drying, compression of the stream to a large extent devoid of moisture, condensation of the CO_2 stream and separation of noncondensable gases (such as N_2, O_2, Ar). Flue gas drying reduces the risk of gas pipelines corrosion (including the acidic corrosion resulting from the fact that both CO_2 and SO_2 gases are acidic) and allows to avoid the danger of ice and/or hydrates formation. In order to remove noncondensable gases from the flue gas, additional physical separation or distillation process is required. In this process (after drying), CO_2-rich flue gases are subjected to partial liquefaction. The need for removal of the aforementioned gases is mainly due to the fact that the presence of these pollutants significantly changes thermodynamic properties of the stream (including phase equilibrium at the vapor-liquid line and thus the parameters of the boiling and condensation point), which in turn affects the conditions of the flue gas stream processing. The presence of impurities entails the change in enthalpy, entropy and heat capacity of the CO_2-rich mixture, and thus in the energy consumption of the separation process. Compared to the pure CO_2 stream, the are containing noncondensable gases, is characterized with an increase of boiling and condensation pressure of the mixture. The composition of gas (and thus the share of particular pollutants) determines the ease of separation of these gases from the stream of CO_2. Therefore making in the calculations it is important to know the flue gas composition and to select suitable computational methodology, as well as to know the parameters of the captured CO_2 stream at the outlet of the compression installation. However, it is difficult to find in the literature precise CO_2 purity requirements to be fulfilled after the capture process. Some guidelines for impurities content in a stream of transported CO_2 can be found, among others, in [9–12]. Most frequently they are based on the USA experience in the enhanced oil recovery (EOR) technology or food industry. When determining the requirements for CO_2, the impact of all impurities on particular elements of the capture, transport and storage installation and the cost of the entire process should be taken into account. Currently, the main method of treating carbondioxide captured from the power plants is geological sequestration. Due to the absence of established guidelines for the sequestration, many different values can be found in the literature. In [12] the division into

three specifications is proposed, which differ in the purity of CO_2, which can be medium, high or very high. The summary is provided in Tab. 1.

Table 1. Guidelines concerning captured CO_2-rich stream composition before transport.

Share (vol.)	Medium purity	High purity	Very high purity
CO_2	> 95%	> 99.5%	> 99.5%
N_2+O_2+Ar	< 5%	< 10 ppm	< 10 ppm
H_2O	< 10 ppm	< 10 ppm	< 10 ppm
NO_x	< 1500 ppm	< 1500 ppm	< 100 ppm
SO_x	< 1500 ppm	< 1500 ppm	< 100 ppm
CO	< 100 ppm	< 10 ppm	< 10 ppm

Obtaining such levels of impurities content is not an easy task, especially on industrial scale (capturing CO_2 from the flue gas stream an power plant). Thus, what is mainly determined at present, are the recovery rate (which part of CO_2 compared to the amount in the flue gas has to be captured) and the purity of carbon dioxide. Both of these indicators should not be less than 90%.

In order to meet the requirements for carbon dioxide prior to its transport and storage, it is necessary to remove water and other impurities (mainly nitrogen, oxygen, argon and sulfur dioxide). For this purpose, a variety of methods can be used, including primarily physical separation, but also the cryogenic methods [13–15].

3 Main assumptions for calculations and evaluation indices of the separation process

This paper presents the analysis of the flue gas drying and purification installations in a coal-fired power plant operating in oxy-fuel combustion technology as well as of a compression installation for CO_2-rich stream prior to transport. For this purpose, appropriate numerical models were built in the commercial engineering simulation software Aspen Plus. The analyses were initially conducted separately for each installation, and then, after putting together all the individual installations for the entire flue gas conditioning system.

3.1 Assumptions for the models

For the analysis, the composition and the parameters of the flue gas arising in a pulverized hard coal-fired 460 MW power plant with an oxy-boiler were adopted.

The gross efficiency of the system is equal to 47.44%, and the auxiliary power of the steam-water cycle is 34.5 MW. The description of the system can be found in [16,17]. These data are summarized in Tab. 2 and relate to the flue gas at the inlet to the CO_2 processing installation, after initial drying and separation of the recycle stream.

Table 2. Main parameters of flue gas assumed in the calculations.

Quantity	Value	Unit
Flue gas stream	123.13	kg/s
Flue gas pressure	101.33	kPa
Flue gas temperature	46.07	°C
Flue gas enthalpy	27.53	kJ/kg
Molar share:		
CO_2	78.75	%
O_2	4.99	%
N_2	5.27	%
SO_2	0.98	%
H_2O	10.00	%

The analyzed models of the drying, capture and compression installation of the flue gas rich in CO_2 were built in the Aspen Plus software [25]. In the first stage of the analysis, in order to verify and optimize each system, individual systems were modeled separately as independent installations, and then they were combined into a whole. The results of the calculations were compared mainly qualitatively (due to the lack of full data allowing for comparison with experimental data or results of modeling) but also quantitatively (for the conditions in which full-enough data were gathered) with the data available in the literature, e.g., [13,18]. The obtained results showed good agreement with the literature data.

In the calculations, it was assumed that the captured carbon dioxide will be transported via pipelines to the storage place and then will be sequestrated underground. However, these parts of the carbon capture and storage installation were not modeled here. It was only assumed that the composition of the CO_2 after drying, purification and compression should fulfill the requirements put on the CO_2-rich stream. Basing on the basis of on [12], it was assumed that the composition of the carbon dioxide stream before transport and sequestration should fulfill the following requirements: CO_2 >95%, N_2+O_2+Ar<5%. It should

however be stressed that there are no precise data concerning requirements for the composition of the CO_2 stream before its transport and the selected data are exemplary.

In order to accurately describe the behavior of carbon dioxide in changing conditions (pressure, temperature), application of the classical ideal gas equation (Clapeyron equation) is insufficient, especially due to the fact that CO_2 in the analyzed systems appears in gaseous, liquid and supercritical state. Therefore, the model used real gas equations of state. For drying and purification installation, the Soave-Redlich-Kwong (SRK) equation of state was implemented [19], while in the compression installation, the Benedict-Webb-Rubin-Starling (BWRS) equation, which better reflects the behavior of CO_2 in the supercritical state, was used [20].

Before transport and storage the captured carbon dioxide has to be compressed. Literature does not precisely specify the pressure value, giving only a broad range from 10 to 20 MPa. The analysis assumes that the pressure and the temperature of the CO_2 stream at the outlet of the compression system are equal to 15 MPa and 30 °C, respectively.

3.2 Evaluation indices of the CO_2 conditioning process

Evaluation of the of the separation process, quality regardless of the chosen method of CO_2 capture, is usually made on the basis of the following indicators:

- purity (molar fraction) of carbon dioxide, Y_{CO2}, in the stream transported from the capture installation;
- recovery rate, R_{CO2}, determining the portion of the carbon dioxide in the flue gas flowing out of the capture installation;
- energy intensity of the separation and/or compression process, E_{int}, defining the power required to separate and compress a given stream of CO_2, which is equal to the energy flux necessary to perform the separation and/or compression process of 1 kg/s of CO_2.

Energy intensity was determined separately for each process (i.e., drying, purification and compression), and globally for the whole conditioning system.

4 Results of the calculations

4.1 Drying installation

The drying installation is needed to remove a substantial amount of water present in the flue gas after the combustion process. The simplest drying installation consists of a compressor, in which gases are compressed to the required pressure, heat exchanger, in which cooling of the gas after the compression process proceeds and a phase separator, in which the separation of gaseous and liquid phase takes place. Such single-stage drying is usually not sufficient to give satisfactory results, thus, a second stage is often implemented, consisting of the same components as the first one. The analysis described in this paper uses a two-stage system shown in Fig. 2.

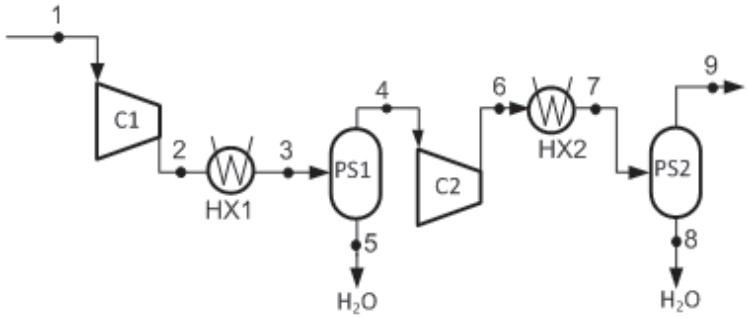

Figure 2. Scheme of a two-stage drying installation; C– compressor, PS – phase separator, HX – heat exchanger.

The main operation parameters were adopted for the calculations based on the previous studies of the drying process made by the author. It was assumed that the final pressure of the compressed gas (after leaving compressor C2, Fig. 2) is around 3 MPa, and the pressure ratio is evenly distributed on both compressors (and equals 5.44). It is a rational compromise between the energy requirements of the drying process and the efficiency of the process. It was also assumed that after the process of isentropic compression in compressors C1 and C2, the streams are cooled in the water coolers to the temperature of 20 °C. Phase separation is an isothermal and adiabatic process. The process conducted in such a way allows for the removal of 99.2% of water. The molar fraction of H_2O in stream 9 (at the exit of the drying installation) is 899 ppm, while the share of CO_2 increases, as compared to the input stream, to 87.4% (by 8.65 pp). Energy demand of the drying installation, related to the separated stream of water (sum

of streams 5 and 8) is equal to 1.91 kWh/kgH_2O. It should be noted that the obtained share of water in the stream directed to further conditioning is higher than required. For example, in [9,12], it represents the level of 50 ppm or 10 ppm, respectively. In order to achieve lower levels of the water vapor content in the flue gas supplied to the CO_2 purification installation, it is necessary to cool the flue gas to a significantly lower temperature (which is associated with high energy input, and is not able anyway to provide the required level of H_2O content). Other methods of separation can also be used (e.g., absorption, adsorption, or active dehydration using trietyleneglycol (TEG)) [9]. However, these methods require additional amounts of energy to be brought to the regeneration process and were not considered in the described work.

4.2 Cleaning installation of the CO_2-rich flue gas

The dried flue gas in the oxy combustion systems consists mainly of CO_2, but also contains other compounds, primarily atmospheric gases (nitrogen, oxygen, argon) and trace impurities (sulfur dioxide, nitric oxides or carbon monoxide). These gases are often referred to as non-condensable gases. The initial composition gas after leaving the drying installation (point 9 in Fig. 2), which was assumed for further calculations, is presented in Tab. 3.

Table 3. Main stream parameters at the inlet to the purification installation.

Quantity	Value	Unit
Flue gas stream	117.65	kg/s
Flue gas pressure	3000	kPa
Flue gas temperature	20.0	°C
Molar share:		
CO_2	87.40	%
O_2	5.50	%
N_2	5.90	%
SO_2	1.10	%
H_2O	899	ppm

The simplest method of separation of noncondensable gases is physical single-stage phase separation. In this method, the CO_2-rich stream is compressed and then cooled, which causes liquefaction of the carbon dioxide stream. It is then separated from other components in a phase separator. This is technically the simplest method, but cannot usually achieve high CO_2 purity and recovery rates,

and therefore the second stage of phase separation or a distillation column installation are usually applied. Additionally, the entire process of separation takes place in the so-called "cold box". In the cold box, very effective, multi-stream heat exchangers (BAHX) brazed aluminum heat exchangers are used, allowing achievement of as low a temperature difference between the streams exchanging heat as 1 K.

Within the cold box, the equipment required in the process, primarily the heat exchangers and phase separators or distillation columns, are closed. Dependently on the required CO_2 purity different configurations of the system are used. To obtain the highest purity distillation columns are applied instead of phase separators. For the analysis described in this paper, a system as shown in Fig. 3 was built. The analyzed installation is composed of two stages of the CO_2 pu-

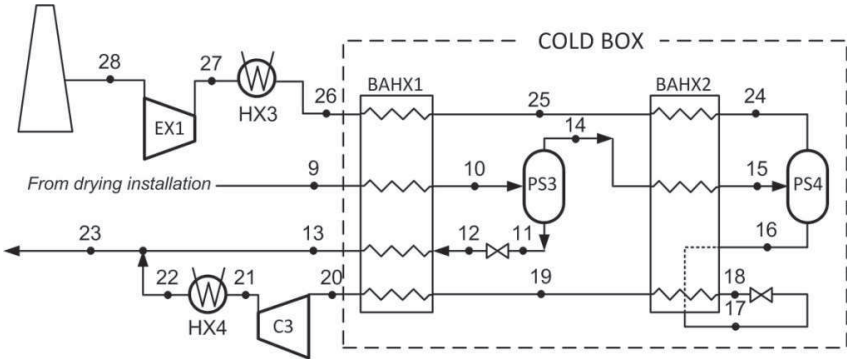

Figure 3. Scheme of flue gas cleaning installation; C – compressor, PS – phase separator, BAHX – multi-stream heat exchanger, EX – turbine.

rification. Therefore, there are two BAHX exchangers and two phase separators within the cold box. Additionally, in order to ensure cooling in the system, high pressure streams are directed in throttle valves. In the considered system, the CO_2-rich flue gases from the drying installation (see Tab. 3) flow to the BAHX1 heat exchanger, in which they are cooled to the temperature of -30 °C (243.15 K), exchanging heat with the streams involved in the process. At this temperature, most of the CO_2 liquefies. The phases are separated in the phase separator PS3. The gas phase, still containing a significant amount of CO_2 is further cooled to the temperature of -55 °C (218.15 K) in BAHX2 heat exchanger, while the liquid phase is expanded to the pressure of 1.8 MPa and directed through the heat exchangers to the compression installation of before further transport to the storage place. Separated in phase separator PS4 gas phase, to a large extent devoid of carbon dioxide, flows through the heat exchangers, and then is further heated,

optionally expanded in expander EX1 and discharged into the atmosphere.

The most important parameters of the streams allowing to obtain a certain level of CO_2 purity are temperature and pressure of the stream in different points of the installation. The influence of these parameters in selected points of the carbon dioxide processing unit (including both drying and purification installation) in a simplified installation without a cold box was presented in another paper of the author [21]. The model presented in this paper was built basing on the results of these calculations in order to obtain the required CO_2 purity, while reaching as high recovery rate as possible. Stream parameters in different points of the process were determined for such a system. The most important results concerning temperature, pressure, flow and composition in the selected points of the process (marked according to Fig. 3) are summarized in Tab. 4.

Table 4. Main parameters of the selected streams in the purification installation.

Parameter	Temperature	Pressure	Flow	Molar share				
				CO_2	H_2O	N_2	O_2	SO_2
Point	°C	bar	kg/s	%				
10	-30.0	29.2	117.647	87.4	911*	5.9	5.5	1.1
11	-30.0	29.2	97.710	95.1	0.1	1.3	2.2	1.3
13	8.5	18.0	97.710	95.1	0.1	1.3	2.2	1.3
14	-30.0	29.2	19.936	55.1	7*	25.0	19.8	513*
16	-55.0	29.2	10.128	94.2	15*	2	3.7	0.1
17	-41.8	29.2	10.128	94.2	15*	2	3.7	0.1
18	-54.3	9.7	10.128	94.2	15*	2	3.7	0.1
19	-41.8	9.7	10.128	94.2	15*	2	3.7	0.1
20	8.5	9.7	10.128	94.2	15*	2	3.7	0.1
21	66.4	18.0	10.128	94.2	15*	2	3.7	0.1
22	20.0	18.0	10.128	94.2	15*	2	3.7	0.1
23	9.5	18.0	107.84	95.0	0.1	1.4	2.3	1.2
24	-55.0	29.2	9.809	24.2	11**	43.2	32.5	10*
28	24.2	11.0	9.809	24.2	11**	43.2	32.5	10*

* value expressed in ppm. ** value expressed in ppb

It results from the calculations that for the assumed purity of the captured CO_2 equal to 95%, the recovery rate is equal to 97.1%. Energy intensity of the drying process results almost exclusively from the need to drive compressor C3. In the analyzed case, this power was equal to 473.7 kW, which recalculated on a stream of one kg/s of captured CO_2, gives the value $E_{int,CPU} = 1.28$ kWh/tCO_2. It should be noted, however, that there is a possibility of installing a turbine (EX1)

to use the flue gas stream released to the atmosphere (point 27, Fig. 3). The power output from the turbine calculated for this case is 2620.7 kW. Taking into account this value in the calculation of energy intensity of the purification process, it gives a negative value equal to -5.78 kWh/tCO_2 (which means, that the electricity input is lower than output). However, it should be stressed, that this concerns only this part of the whole CO_2 processing installation.

4.3 Carbon dioxide compression installation

The last element used in the preparation of the carbon dioxide preparation for the transport is the compression installation. The analysis assumes that due to the relatively high CO_2 pressure at the inlet to the installation (point 23, see Tab. 4), only a two-sections compressor is used. Pressure ratios of the individual sections are equal and amount to 2.89. Isentropic efficiency of each section was assumed as 0.8 and 0.7, respectively, while mechanical efficiency of the generator was 0.98. It was also assumed that there is a cooler between the sections, in which the CO_2 stream is cooled to the temperature of 20 °C. After leaving the second section of the compressor (before transport), the stream is cooled to the temperature of 30 °C. The final CO_2 pressure is 15 MPa.

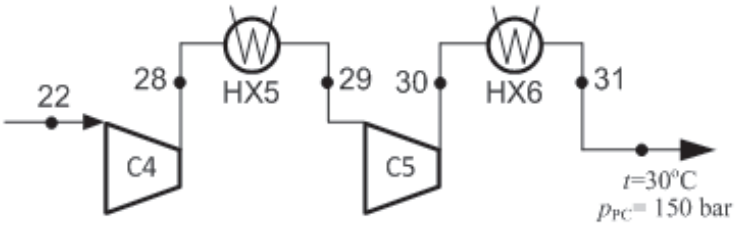

Figure 4. Scheme of the compression installation of captured CO_2; C – compressor, HX – heat exchanger.

The analysis shows that for the assumptions made, the total power of compressors C4 and C5 is 15.625 MW, which recalculated on the captured CO_2 stream gives the energy intensity of the compression process equal to 41.57 kWh/tCO_2. The total stream of cold brought to heat exchangers HX5 and HX6 amounts to 39.981 MW (387.45 kJ/kgCO_2). Energy intensity of the compression process can be reduced by applying more sections of compression, or by the use of a pump of liquid CO_2 (instead of one section of compressor). In another case of the compression process analyzed by the author, the use of pumps allowed to reduce the energy demand by about 17% [22].

4.4 Energy intensity of the whole CO_2 processing installation in the oxy-combustion system

The CO_2 processing system proposed in this paper includes, as it has been described earlier, drying, purification and compression of CO_2-rich stream prior to its further transport. The model included all the components of particular installations integrated in one system. Energy intensity of each installation as well as of the whole system, presented per unit stream of the captured CO_2, are summarized in Tab. 5. This table includes also the case with energy recovery in turbine EX1 mounted on the stream released to the atmosphere (EX1, Fig. 3).

Table 5. Energy intensity of the CO_2 processing installations in the oxy-combustion system.

	Energy intensity, kWh/tCO_2	
	with turbine EX1	without turbine EX1
Drying	100.63	
Purification	-5.78	1.28
Compression	41.57	
Total	136.42	143.48

In the analyzed case, the most energy-intensive process is flue gas drying. It results from the fact that in this installation, the pressure of the flue gas stream is increased to a relatively high value, i.e. 30 bar. This pressure is the driving force of the purification process, and therefore energy intensity of this system is negligibly small. For the same reason the stream pressure at the inlet to the compression installation is also relatively highand therefore the required pressure ratio of the CO_2 compressor slower. The total energy requirement for drying, purifying and compressing of the carbon dioxide stream in the analyzed oxy-combustion system is equal to 143.48 kWh/tCO_2, while recovering of a part of energy through the expansion of the flue gas stream can reduce the energy intensity by about 5%. Further reduction of the energy consumption can be considered during the optimization of the whole process, especially while integrating this installation with other elements of the oxy-combustion system.

One method for reduction of the energy intensity of the whole integrated oxy-system can be recycling of the flue gases, exhausted to the atmosphere (after expanding in turbine EX1), into the boiler. This stream (point 27 in Fig. 3) contains 32.5% oxygen, which gives a stream of pure O_2 equal to 3.077 kg/s. In the case of recirculation of this stream to the boiler, less oxygen could be sup-

plied to the combustion process from the air separation unit, which is the most energy-intensive installation in oxy-combustion systems. In the system with the power output of 420 MW, the demand for pure oxygen for combustion is around 90 kg/s. Therefore, the stream of oxygen recovered in CO_2 capture installation constitutes up to more than 3% of the total flow of oxygen supplied to the boiler. However, in order to quantitatively evaluate the effectiveness of this solution, a detailed technical and economic analysis of the whole system should be carried out.

In the analyzed system, for the assumed CO_2 purity of 95%, a high recovery rate was achieved, being equal to 97.1%, which is consistent with the currently imposed guidelines, set equal or higher than 0.9. Achieving the required CO_2 recovery rate is not a problem in oxy-combustion systems. However, it may prove problematic to achieve the required levels of impurities content, e.g., in accordance to the ones presented in Tab. 1. Achieving such low gas content value will require the use of chemical methods, which will increase the energy intensity of the purification process.

In order to calculate the decrease of the efficiency and power of the analyzed 460 MW oxy plant due to the implementation of the CPU unit, the auxiliary power rate of this unit was calculated from the formula

$$\delta_{CPU} = \frac{N_{CPU}}{N_{el}} , \tag{1}$$

where N_{CPU} is the total power of the CO_2 processing unit, and N_{el} is the gross power of the plant. The stream of the captured CO_2 considered to obtain the results presented in Tab. 4 is of 103.24 kg/s, which gives the total power demand of the carbon dioxide processing unit equal to 52.3065 MW. Thus, the calculated auxiliary power rate δ_{CPU} is equal to 0.1137.

Gross efficiency of the power plant is calculated from the equation:

$$\eta_{el,gross} = \frac{N_{el}}{Q_d}\eta_k , \tag{2}$$

where:

Q_d – heat supplied to the cycle, kW
η_k – thermal efficiency of the boiler,
N_{el} – electric power produced in the power plant, kW.

Net efficiency of the power plant has to be calculated taking into account auxiliary power $N_{el,AUX}$ of all the installations and the auxiliary power of the steam-water cycle, which can be expressed by auxiliary power rate δ_{AUX} and δ_{SC}, respectively.

Thus, the net efficiency can be calculated from the equation:

$$\eta_{el,net} = \eta_{el,gross}(1 - \delta_{SC} - \delta_{AUX}) \; . \tag{3}$$

For the calculations of the net efficiency, only the power demand of the steam-water cycle and the carbon dioxide processing unit were taken into account (the auxiliary power of other installations, e.g., of the air separation unit was not calculated). Thus, only the auxiliary power rate of the CPU installation and the steam-water cycle was considered. The auxiliary power rate of the steam-water cycle of the analyzed unit is equal to 0.075. The calculated net efficiency can be used to determine the efficiency decrease due to the implementation of the CPU installation. For this reason, the δ_{AUX} rate in the Eq. (3) should be replaced with the δ_{CPU} rate, calculated from Eq. (1). The calculated net efficiency of the system without the CPU installation is equal to 43.88% and with the use of installation it takes value of 38.49%. It means that the efficiency decrease caused by the implementation of the carbon capture and compression unit is equal to 5.39 pp.

5 Discussion and conclusions

Reducing CO_2 emissions from energy systems by the use of carbon capture and storage methods, though often questionable, is slowly becoming a necessity. In this context, oxy-systems are seen as promising and competitive with capture systems using precombustion (integrated gasification combined cycle (IGCC) systems) or postcombustion technology. Their main advantage over other perspective systems is reduction of energy intensity of the CO_2 capture process, particularly when compared to the postcombustion methods. Depending on the technology of carbon dioxide capture and the final pressure of CO_2 before transport, energy consumption is usually in the range 100–150 kWh/tCO_2, while in the case of the conventional systems (with postcombustion method using amine absorption) the energfy for capture process (without compression to the pressure required for transport) is 180–320 kWh/tCO_2 [23,24]. However, it should be noted that in the case of oxy-combustion systems, there is also the need to build the installation of air separation unit, which due to the very high energy demand, significantly reduces the efficiency of the entire system.

The paper presents the results of research conducted with a view to build a numerical model of CO_2 capture installation in an oxy-combustion power plant, used for flue gas drying and purification, as well as for compression of CO_2-rich stream to the value of pressure required for transport and sequestration. The

process of transport and storage was not analyzed here. Energy intensity of the whole system used in the preparation of CO_2 to transport and designed to reach 95% purity of the captured CO_2, was equal to 143.48 kWh/tCO_2. In the analyzed case, the efficiency decrease of the whole oxy system caused by the implementation of the carbon capture, purification and compression installation (to the pressure of 15 MPa) was equal to 5.39 pp. It can be decreased by heat regeneration in the cycle, optimization of the separate components and of the whole unit, as well as by integration of the different components of the oxy system.

In order to decrease the energy intensity of the process, it was proposed to recover part of power by carrying the stream, to a large extent devoid of carbon dioxide, to expand in the turbine. Such treatment reduces the energy consumption by 7.06 kWh/tCO_2. Further reduction of the energy can be obtained through the integration of this system with other components of the integrated oxy-system, e.g. by heat recovery from the interstage cooling of the flue gas or carbon dioxide stream. There can also be considered, the use of liquid CO_2 pumps or the increase in the number of compression sections [22]. The possibility high purity (e.g. greater than 99.5%) oxygen production can also be analyzed, which will reduce the amount of pollutants in the exhaust stream and thereby provide higher purity gas at the entrance to the CO_2 processing installation. However, due to the fact that the currently used cryogenic methods for obtaining such high oxygen purity require very large energy inputs, in order to assess viability of the proposed solutions, energy intensity of the oxy-system as a whole should be considered, together with the ASU and CO_2 processing installation.

It results from the analysis presented in this paper that obtaining CO_2 purity and recovery rate at the required level (90%) is not a significant problem in oxy-fuel systems, and the capture process is associated with significantly lower energy input in case of the mentioned process of CO_2 capture than while using the post-combustion methods. However, obtaining such levels of pollutants as suggested in [9,12], will require additional separation methods, including in particular separation of H_2O, and thus, additional energy input. Still, it applies not only to oxy-combustion systems, but to all capture methods. It is, therefore, important to precisely determine the required composition of CO_2 for further management (in particular for geological storage).

It is needed to conduct a detailed economical analysis of the possibility of implementation of a CPU installation to oxy-systems. Such an analysis has not been conducted in the present work due to the fact that the main aim of the work was to analyze the CPU installation as a stand-alone component, not being integrated with other components of the oxy-system. The economic analysis

should take into account the whole oxy-system and integration of different components of the unit (which will allow to lower the cost of oxygen production and CO_2 capture), as well as the existing law and commitments, such as the emission trading scheme. Such an analysis will be conducted by the author in the future.

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Modelowanie i analiza układu kondycjonowania CO_2 metodą separacji fizycznej w nadkrytycznym bloku węglowym o mocy 460 MW pracującym w technologii oxy-spalania

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

Idea układów oxy-spalania polega na spalaniu paliwa w atmosferze wysokiej czystości tlenu. Spaliny z tego typu układów składają się prawie wyłącznie z dwutlenku węgla i wody, a zatem koszt przygotowania CO_2 do transportu do miejsca składowania jest niższy niż w układach konwencjonalnych. Jednak w praktyce, obok CO_2 i H_2O w spalinach pojawiają się także inne związki, w tym np. argon, dwutlenek siarki, azot czy tlen, które muszą zostać odseparowane przed transportem CO_2. Najczęściej stosowanymi metodami separacji tych gazów ze strumienia CO_2 jest separacja fizyczna. W celu określenia energochłonności procesu separacji zbudowany został model numeryczny układu wychwytującego dwutlenku węgla ze spalin bloku węglowego pracującego w atmosferze tlenowej. W tym celu wykorzystano program Aspen Plus. Obliczenia prowadzono dla układu o mocy 460 MW. W artykule przedstawiono wyniki obliczeń energochłonności układu z uwzględnieniem takich parametrów, jak czystość czy stopień odzysku CO_2. Z analiz wynika, że osiągnięcie wysokiej czystości i stopnia odzysku separowanego z gazów spalinowych dwutlenku węgla nie jest trudne, jednak osiągnięcie wymaganych poziomów zawartości innych związków może być problematyczne. Zaproponowano również sposoby obniżenia energochłonności instalacji wychwytu CO_2.