

archives
of thermodynamics

Vol. 35(2014), No. 4, 55–68

DOI: 10.2478/aoter-2014-0033

Analysis of thermodynamics of two-fuel power unit integrated with a carbon dioxide separation plant

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Abstract The article presents the results of thermodynamic analysis of the supercritical coal-fired power plant with gross electrical output of 900 MW and a pulverized coal boiler. This unit is integrated with the absorption-based CO₂ separation installation. The heat required for carrying out the desorption process, is supplied by the system with the gas turbine. Analyses were performed for two variants of the system. In the first case, in addition to the gas turbine there is an evaporator powered by exhaust gases from the gas turbine expander. The second expanded variant assumes the application of gas turbine combined cycle with heat recovery steam generator and backpressure steam turbine. The way of determining the efficiency of electricity generation and other defined indicators to assess the energy performance of the test block was showed. The size of the gas turbine system was chosen because of the need for heat for the desorption unit, taking the value of the heat demand 4 MJ/kg CO₂. The analysis results obtained for the both variants of the installation with integrated CO₂ separation plant were compared with the results of the analysis of the block where the separation is not conducted.

Keywords: CO₂ separation; Thermodynamic analysis; Two-fuel power unit

Nomenclature

\dot{E} – chemical energy flux, MW
 N – power, MW

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- \dot{m} – mass flux, kg/s
 R – recovery ratio

Greek symbols

- η – efficiency, %

Subscripts

- aux – auxiliary power
 B – gross
 $BPST$ – backpressure steam turbine
 ch – chemical energy
 c – coal
 el – electrical
 g – gas
 GT – gas turbine system
 n – net
 SEP – carbon dioxide separation unit
 ST – steam turbine

1 Introduction

The energy sector using fossil fuels such as coal and lignite, contributes to the devastation of the environment and, according to [1] is responsible for slightly more than 30% of anthropogenic greenhouse gas emissions in the EU member countries. Policies on climate and energy issues definitely move towards decarbonisation of the economies of member countries. Efforts have also been made to develop technologies with low carbon dioxide emissions, or allowing to decrease it. Technical solutions possible to implement are the carbon dioxide (CO₂) capture plants, including installation utilizing chemical absorption method. This technology can be adapted in the context of functioning power unit, or it may be a part of the newly designed installation. In each case, the system must be supplied with the heat required for the process of desorption. Possible solutions to this problem are supplying heat by: a) steam extracted from the steam turbine, b) from an external source. The first mentioned solution is a classic solution. This solution leads to a reduction of the power of turbine and consequently a significant reduction in the efficiency of the unit. An extensive case study is given in [2,3]. In order to evaluate alternative heat supply method for carbon dioxide separation plant the systems based on a gas turbine unit were analyzed. Two variants were developed. In the first the heating medium directed to the separation plant is saturated steam generated by the evaporator supplied with exhaust gases from the gas turbine. In the second one the gas tur-

bine system implements the integrated circuit with a back-pressure steam turbine. This system, although it requires the use of a gas turbine with a higher capacity allows for more efficient use of natural gas.

The subject of the paper is the integration of these systems with supercritical power plant with gross capacity 900 MW. The purpose of inclusion in the system with the gas turbines is to supply the heat to separation plant which uses chemical absorption method. Thermodynamic analysis was carried out with the assumed energy intensity of the desorption process at the level of 4 MJ/kgCO₂.

2 Description of the supercritical power unit

The primary system, which was integrated with the installation of the separation of carbon dioxide is a supercritical unit whose diagram is shown in Fig. 1. The gross capacity of the unit is 900 MW. Technological line

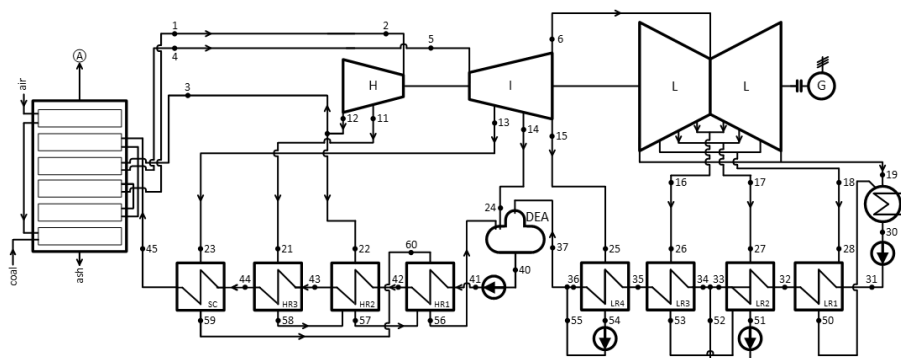


Figure 1: Diagram of a supercritical coal-fired unit with a power of 900 MW: H – high-pressure part, I – intermediate- pressure part, L – low-pressure part, SC – the steam cooler, HR1-HR3 – high-pressure heat exchangers, DEA – deaerator, LR – low-pressure regenerative heat exchangers, G – generator.

consists of: pulverized coal-fired steam boiler (the lower heating value of coal: 23.93 MJ/kg, moisture: 0.090, ash: 0.200, C: 0.599, H: 0.038, O: 0.050, N: 0.012, S: 0.010). The unit consists of a boiler equipped with a single reheater, an extraction-condensation steam turbine, which consists of the high-, medium-, and low-pressure part, with the double-flow in the low-pressure section. Steam extracted from the turbine is directed to the steam cooler (SC), three regenerative high-pressure heat exchangers (HR), deaerator (DEA) and four low-pressure regenerative heat exchangers (LR).

Table 1: Assumptions for calculations.

Item	Value	Unit	Item	Value	Unit
Deaerator operating pressure	1.15	MPa	Pressure drop in steam pipe between steam cooler and regenerative heat exchanger HR1	1.0	%
Condenser operating pressure	0.005	MPa	Pressure drop of water in regenerative heat exchangers and steam cooler	1.0	%
Pressure at outlet of condensate pump	2.2	MPa	Pressure drop of working medium in steam boiler	4.2	MPa
Feed water temperature	310	°C	Pressure drop of steam in reheater	0.3	MPa
Internal efficiency of stage groups of steam turbine part H	90.0	%	Pressure drop in reheated steam pipes	1.7	%
Internal efficiency of stage groups of steam turbine part I	92.0	%	Temperature increase of condensate in low-pressure regenerative heat exchangers	120.7	K
Internal efficiency of stage groups of steam turbine part L	85.0	%	Temperature increase in regenerative heat exchanger HR1	41.9	K
Internal efficiency of last stage groups of steam turbine part L	80.0	%	Temperature increase in regenerative heat exchanger HR3	28.4	K
Efficiency of the generator	98.8	%	Temperature increase in steam cooler	5.0	K
Mechanical losses of turbine	0.32	MW	Terminal temperature difference in regenerative heat exchangers LR1, LR2, LR3 and LR4	3.0	K
Internal efficiency of pumps	85.0	%	Terminal temperature difference in regenerative heat exchangers HR1, HR2 and HR3	2.0	K
Efficiency of regenerative heat exchangers and steam coolers	99.5	%	Drain cooling approach temperature in regenerative heat exchangers HR1, HR2 and HR3	10	K
Pressure drop in steam pipes of steam fed to regenerative heat exchanger and steam cooler	2.0	%			

3 Characteristics of carbon dioxide separation unit

Among the methods under consideration which allow separation of carbon dioxide from the flue gas is the chemical absorption method using a monoethanolamine (MEA) as aqueous sorbent. It is an option of significant potential, mainly due to its high commercial readiness. The contemplated system consists of two columns: the first column, i.e., an absorber, wherein the scrubbing MEA compound reacts with CO₂ in exhaust gas, and the

second column, i.e., a stripper column, where CO₂ saturated MEA solution is subjected to heat for the regeneration process. This heat is supplied to the installation from the outside. In the first column MEA solution absorbs CO₂. Exhaust devoid of gas (according to the assumptions in 90%) leave the column and enter the atmosphere. In the processing of flue gases before CO₂ removal system, deep cleansing is necessary, including the deep desulfurization, because sulfur reacts with the MEA compounds forming fixed salts. MEA solution which was saturated with carbon dioxide is leaving the absorber column at a lower portion, and is directed to the heat exchanger and then to the stripper column. In this column, after reaching the internal temperature of 125 °C, followed by release of CO₂, the carbon dioxide stream exits the column, together with a substantial amount of water vapor. The final separation of CO₂ is carried in the condenser. The CO₂ stream is then directed to the compression plant, whose role is to compress the fluid to a pressure of 15 MPa. After cooling, the medium is liquefied and transported to the storage area.

To realize the desorption process it is necessary to supply the stripper column (indirectly through a reboiler) with heat. In the classical solutions, analyzed by authors [2,3], the heat is applied with a steam taken from the steam turbine from the power unit. The advantage of this solution is that no additional systems are necessary which lowers the investment costs. In the literature alternative methods of supplying the heat for the desorption process are examined. The production of heat in an external source powered by a biomass boiler is analyzed in [4]. However, in [5–7] variant in which heat is extracted from the flue gas leaving the gas turbine assembly is analyzed. A more complex variant is the subject of analysis in this article.

For the purposes of analysis it is assumed that the integration of the power unit characterized in Section 2 with separation plant consists of bringing only flue gas leaving the boiler to CO₂ separation plant (the connection of two systems indicated in Figs 1 and 2 with the letter A). It was assumed that in the separation plant there is a four-section compressor with built-in inter-section coolers. It was assumed that the gas in inter-section coolers is cooled to a temperature of 40 °C, and the heat is dissipated in the atmosphere. Finally pressurized to 15 MPa carbon dioxide is cooled in a heat exchanger built-up at the outlet of the compressor.

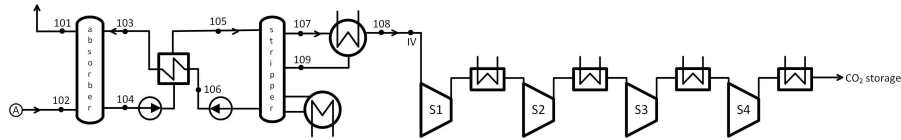


Figure 2: System design of chemical sequestration installation. Drawing reference: A – exhaust gas stream after cooling, S1-S4 – section compressor with built-in inter-section coolers, 101 – exhaust gases without CO₂, 102 – exhaust gases undergo absorption, 103, 106 – regenerated sorbent (MEA), 104, 105 – CO₂ saturated sorbent, 107 – mixture of steam and CO₂, 108 – CO₂ stream transported to the compression section, 109 – condensate.

4 Variants of the external heat supply of carbon dioxide separation plant

The first integration scenario under consideration is referred to as A. This is a simple arrangement consisting of a gas turbine plant and evaporator. The installation of the gas turbine comprises: a compressor with pressure ratio equal to 20, combustion chamber supplied with fuel of the following composition: CH₄: 0.9733, N₂: 0.0086, C₂H₆: 0.0081, C₃H₈: 0.0046, CO₂: 0.0028, C₄H₁₀: 0.0026, and a turbine expander. The evaporator generates saturated steam, which is fed to the reboiler in the separation plant. A circuit diagram is shown in Fig. 3. Top characteristic values used in the calculation are summarized in Tab. 2.

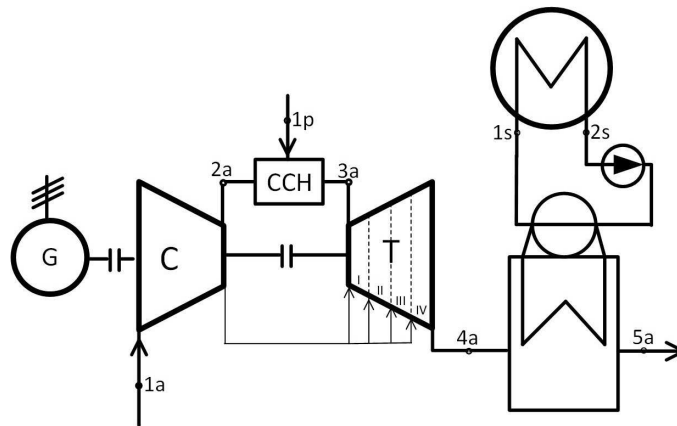


Figure 3: Circuit diagram of the external heat generation system for separation of carbon dioxide according to variant A – gas turbine unit with evaporator: C – compressor, CCH – combustion chamber, T – turbine, G – generator.

Table 2: Assumptions for calculations for variant A.

Parameter	Value	Unit	Parameter	Value	Unit
Lower heating value	48.82	MJ/kg	Cooling air ratio, as follows:	0.2	–
			– cooling the first stage expander	0.5	–
Pressure ratio	20	–	– cooling the second stage expander	0.35	–
			– cooling the third stage expander	0.15	–
Ambient temperature	15	°C	Exhaust gas temperature for the combustion chamber	1 430	°C
Ambient pressure	0.1013	MPa	Isentropic efficiency of the expander of the gas turbine	90	%
Fuel temperature	15	°C	Steam stream demand	290	kg/s
Pressure of supply fuel	3.5	MPa	Steam temperature	130	°C
Isentropic efficiency of air compressor	88	%	Steam pressure	270.66	kPa
Efficiency of the generator	99	%			

The second considered option of external heat supply for carbon dioxide separation plant is referred to as B. It is a system consisting of a gas turbine unit and a steam cycle. It was assumed that in the system B the gas turbine operates with the same parameters as in Option A. For additional components that are not found in the case A, it is assumed that the isentropic efficiency of the backpressure steam turbine is 90%, and the superheated steam temperature is 527 °C. Minimum difference of temperatures in heat recovery steam generator (the pinch point) and a water subcooling at the drum inlet (the approach point) are equal to 5K. Gas turbines in the analyzed variants may differ in power output only. Steam cycle consists of heat recovery steam generator and back-pressure steam turbine, whose task is to produce steam for the stripper process. Such cycle diagram is shown in Fig. 4.

Research was carried out for a fixed value of the energy demand for the stripping process, q_{des} , at the level of 4 MJ/kgCO₂. During the thermodynamic and environmental analysis the decision variable was the pressure of supplied steam.

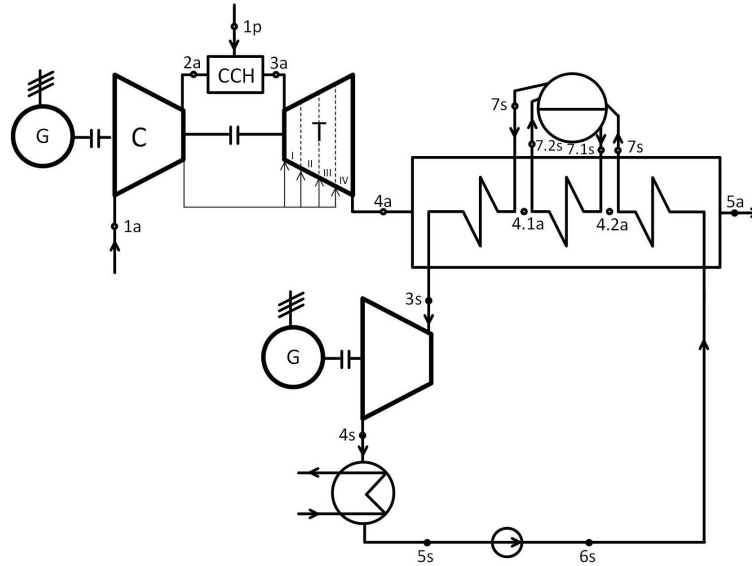


Figure 4: Diagram of an external heat supply system in the carbon dioxide separation plant in accordance with an embodiment of the gas turbine assembly B including heat recovery steam generator and backpressure steam turbine: C – compressor, CCH – combustion chamber, T – turbine, G – generator.

5 Thermodynamic and ecological analysis

The analysis is comparative in nature, and a common part of the analyzed system is the same carbon power unit of 900 MW, the characteristics of which is presented in Section 2. Thus, the values like chemical energy of a flux of coal supplied to boiler, auxiliary power, flux of CO₂ generated by the combustion of coal are the same for both variants. In addition, it is assumed that both variants work with the same installation of separation of carbon dioxide under the same assumptions concerning the separation process such as auxiliary power (the electrical power needed to drive the compressor), and the CO₂ recovery ratio.

5.1 Evaluation indicators

To compare the two variants the indicators defined in Section 5.1 were used. During the analysis the gross efficiency of electricity generation units integrated in accordance with the described variants were determined. These

quantities are defined as follows:

- for variant A

$$\eta_{el,B} = \frac{N_{el,ST} + N_{el,GT}}{\dot{E}_{chc} + \dot{E}_{chg}}, \quad (1)$$

- for variant B

$$\eta_{el,B} = \frac{N_{el,ST} + N_{el,GT} + N_{el,BPST}}{\dot{E}_{chc} + \dot{E}_{chg}}. \quad (2)$$

The important indicator for assessing the thermodynamic effectiveness is the net electricity generation:

- for variant A

$$\eta_{el,N} = \frac{N_{el,ST} + N_{el,GT} - \sum (N_{aux,ST} + N_{aux,GT} + N_{aux,SEP})}{\dot{E}_{chc} + \dot{E}_{chg}}, \quad (3)$$

- for variant B

$$\eta_{el,N} = \frac{N_{el,ST} + N_{el,GT} + N_{el,BPST}}{\dot{E}_{chc} + \dot{E}_{chg}} - \frac{\sum (N_{aux,ST} + N_{aux,GT} + N_{aux,BPST} + N_{aux,SEP})}{\dot{E}_{chc} + \dot{E}_{chg}}. \quad (4)$$

Gross and net efficiency of the external sources producing steam for CO₂ separation process was calculated. Gross efficiency of external sources is defined as follows:

- for variant A

$$\eta_{el,B} = \frac{N_{el,GT}}{\dot{E}_{chg}}, \quad (5)$$

- for variant B

$$\eta_{el,B} = \frac{N_{el,GT} + N_{el,BPST}}{\dot{E}_{chg}}. \quad (6)$$

Net efficiency of external sources is defined as follows:

- for variant A

$$\eta_{el,N} = \frac{N_{el,GT} - \sum N_{aux,GT}}{\dot{E}_{chg}}, \quad (7)$$

- for variant B

$$\eta_{el,N} = \frac{N_{el,GT} + N_{el,BPST} - (\sum N_{aux,GT} + \sum N_{aux,BPST})}{\dot{E}_{chg}}. \quad (8)$$

As a part of ecological analysis, specified index describing the sources of energy in terms of direct CO₂ emissions was calculated. This indicator is a unit of the gas emissions per net unit of generated electricity:

$$\varepsilon_{CO_2} = \frac{(1 - R_{CO_2}) \cdot m_{CO_2c} + m_{CO_2g}}{N_{sum}}, \quad (9)$$

where

$$N_{sum} = N_{el,ST} + N_{el,GT} + N_{el,BPST} - \sum (N_{aux,ST} + N_{aux,GT} + N_{aux,BPST} + N_{aux,SEP}).$$

5.2 Results of analyzes

The results summarized in this section apply to the analyses carried out for two variants of the external power supply of carbon dioxide separation plant at the rate of demand for heat desorption at 4 MJ/kgCO₂. The exhaust gases of coal-fired boiler (point A in Figs. 1 and 2) after purification installations are directed to the separation of carbon dioxide. The analysis assumed that the carbon block is operated at a constant load. Exhaust stream was 833.96 kg/s. Assuming a recovery rate of CO₂ from the stream at 90% steam flow directed to installation of CO₂ capture is 290 kg/s. In case of variant B the analysis was performed at a constant pressure of steam produced in the heat recovery steam generator (the point 4s), equal to 7.913 MPa. This value of pressure provides saturated vapor at the outlet of the back-pressure steam turbine. The results are summarized in Tab. 3.

Comparing the obtained results it can be seen that to produce the same flow rate of vapor for the needs of the stripping process in the case of variant A less chemical energy is required of the gas flow rate than it is in the case of variant B. In the case of variant B due to the greater power of the gas turbine we deal with a much larger flow of exhaust gas generated by burning natural gas. In addition, the fact that these fumes under both variants are not subject to separation translates to the fact that in the case of variant B we deal with the higher rate of carbon dioxide emissions per unit. The next section presents the results of analyses showing the impact of the different characteristics of system performance in a variant B on the value of pressure of steam at the blades steam back-pressure turbine.

Table 3: Thermodynamic and ecological analysis for variants A and B.

Size	Designation	Variant A	Variant B	Unit
Gross power of the coal-fired power plant	$N_{el,ST}$	900.00		MW
Chemical energy flux of hard coal	\dot{E}_{chc}	1907.22		MW
Auxiliary power of coal power unit	$N_{aux,ST}$	67.50		MW
Auxiliary power of separation unit	$N_{aux,SEP}$	49.73		MW
Recovery ratio of CO ₂	R_{CO_2}	90		%
Flux of CO ₂ generated by the combustion of coal	m_{CO_2c}	174.60		kg/s
Rate of chemical energy of gas	\dot{E}_{chg}	1385.67	2096.68	MW
Power of gas turbine	$N_{el,GT}$	536.83	796.65	MW
Gross efficiency	$\eta_{el,B}$	43.61	47.66	%
Net efficiency	$\eta_{el,N}$	40.03	44.63	%
Gross efficiency of external source	$\eta_{el,B}$	38.74	48.09	%
Net efficiency of external source	$\eta_{el,N}$	38.63	47.96	%
Flux of CO ₂ generated by the combustion of gas	m_{CO_2g}	73.68	111.50	kg/s
The unit CO ₂ emission	ε_{CO_2}	201.38	252.78	kgCO ₂ /MWh

5.3 The effect of steam pressure on the operating characteristics of the system according of variant B

The results presented in this section relate to analyses carried out for changes in pressure of steam generated in the heat recovery steam generator. The pressure was varied in the range of 2–16 MPa. Testing proceeded at a constant heat flux supplied to the carbon dioxide separation plant. Figure 5 is a description of the power produced by a system of gas turbine and back-pressure steam turbine.

There is a need to install a gas turbine with more power, which is accompanied by an increase in back-pressure steam turbine power. The increase in back-pressure steam turbine power comes from the increase in enthalpy accompanying decline dispositional expansion of steam in expander. Relations obtained under the change of the power of gas turbine, power of

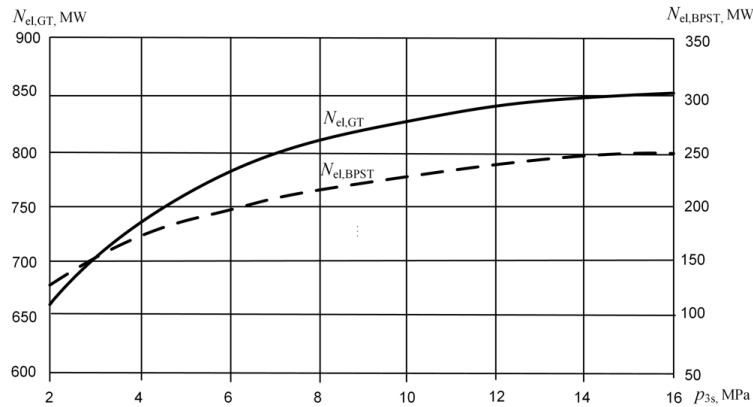


Figure 5: Characteristics of powers of variant B as a function of pressure steam directed to back-pressure steam turbine.

back-pressure steam turbine and gas flow of chemical energy change accompanying the steam pressure translates into performance characteristics as shown in Fig. 6.

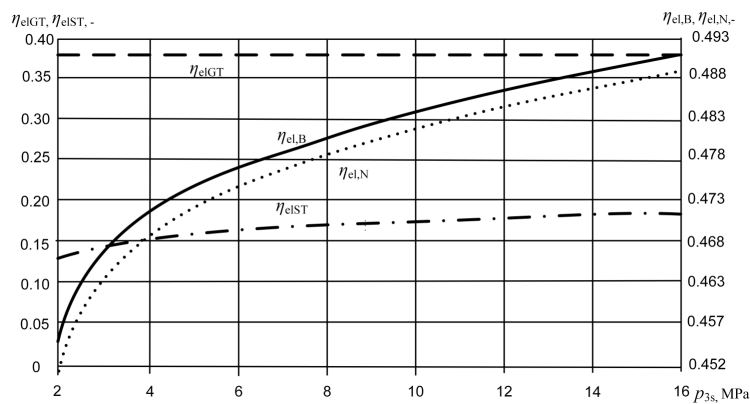


Figure 6: Characteristics efficiencies of power plant integrated with CO₂ separation unit according to variant B as a function of pressure of steam directed to steam backpressure turbine.

The resulting performance characteristics can be related to the efficiency of the reference unit (where the separation of CO₂ is not realized), where in the gross efficiency is 49.1% and the net efficiency is 45.42%.

An important aspect of the analysis of coal-fired power units is the eco-

logical condition considering CO₂ emissions. Value of emission in the case a 900 MW unit with supercritical parameters within which the separation of CO₂ capture is not implemented is 755 kg/MWh. Including separation with the use of a gas turbine system contributes to a significant reduction in the emission factor, but not less due to lack of CO₂ separation from the exhaust of the gas turbine. This ratio is much higher than would be the case with the installation of an integrated block separation in a classical way (83.07 kgCO₂/MWh). After the analysis conducted for the variable pressure of steam in the range of 2–16 MPa values of emissions per unit of emissions was obtained in the range of 245.27–255.75 kgCO₂/MWh.

6 Summary

Variants analyzed in the paper are alternatives in relation to the classical solutions, where the stripping process is carried out by using the steam drawn from the bleeding of steam turbine of power unit. The solution for the existing blocks requires a substantial interference with the construction of the turbine, consisting, e.g., of removal of turbine stages [8]. Adaptation of the newly designed block allows for proper design of the steam turbine for the execution of large extracting of the steam flow rate for stripping. The production process using designed in such a way turbine could prove to be disadvantageous with effectiveness in the event of withdrawal of the process of separation in the future, which could be due to changes in climate policy, or in the case of the implementation of new methods of separation. In view of the foregoing, the use of gas turbine systems for the production of heat required for stripping process may be considered. The advantage of using an external heat source is no interference with the construction of a power unit. But it is important to be aware that the required adaptation of gas turbines of such large powers as in the case of the analyzed variants contribute to a high share of natural gas in the structure of primary energy use within the energy system. Despite the higher efficiency of electricity generation in the block integrated with a separation installation and gas turbine, compared to the reference block, it should be underlined that the achieved efficiencies are far different from high efficiencies that can be achieved in gas turbine combined cycles, i.e. up to 60%. In addition, it should be noted that the obtained values of emissions are only slightly lower than the value that can be achieved in modern gas turbine combined cycle systems, i.e. 330 kgCO₂/MWh. The legitimacy of the integration of

the coal power unit according to the sample in the article variants will be determined by economic analysis.

Acknowledgement The results presented in this paper were obtained from research work cofinanced by the National Centre of Research and Development in the framework of Contract SP/E/1/67484/10 – Strategic Research Program – Advanced technologies for energy generation: Development of a technology for highly efficient zero emission coal-fired power units integrated with CO₂ capture.

Received 9 May 2014

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