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Analysis of the possibilities of steam extraction from a condensing 900 MW turbine for the carbon dioxide separation system

The paper presents the requirements for a carbon dioxide separation system based on chemical absorption in terms of the heat quantity as well as the heating medium needed for the sorbent regeneration. The possibilities of steam extraction from the turbine to supply the carbon dioxide separation system were analyzed. The power plant indicators for diverse sorbents were determined. The possibilities of steam turbine modifications after its integration with the separation system and the changes in the feed water heating system were discussed. The impact of the assumed configuration of the low pressure turbine on the scope of its restructuring was presented. The calculations were performed for a 900 MW supercritical coal-fired condensing unit. Also, the possibility of heat extraction from the boiler exhaust gases for the separation system was considered.

1 Introduction

Recent years have brought intense research on the processes leading to a reduction in carbon dioxide emissions from power engineering systems based on the combustion of fossil fuels. This creates a problem for the Polish power engineering sector, where coal plays the dominant role. In order to further develop coal-based power engineering it is fundamental to meet the more and more stringent requirements concerning allowable carbon dioxide emissions, as well as to use chemical energy more efficiently. Under the European Union Climate and Energy Package [6,7] our country has been obliged to:

- reduce greenhouse gas emissions by 20% compared to the year 1990;
- achieve a 20% share of renewable energy in total energy consumption in the year 2020;

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- improve energy effectiveness by 20% compared to the forecast for the year 2020;
- increase the share of biofuels in the overall consumption of transport fuels to 10%.

The works of the European Parliament resulted in more directives which established, among others, a scheme for greenhouse gas emissions allowance trading in order to reduce the emissions in a cost-effective and economically efficient manner [6], and imposed requirement to build new installations being ‘carbon dioxide capture and storage (CCS) ready’ [7], known as the CCS Directive). The latter introduces the obligation to incorporate a CCS system into the newly-constructed power engineering facilities. At the moment, no commercial technologies of carbon dioxide capture and storage are available, but the CCS directive instructs that the place for this system should be reserved (the so-called ‘capture ready’ obligation).

There are many carbon dioxide separation technologies which include processes of absorption and desorption, as well as membrane and cryogenic separation. Absorption is now used on a greater scale in the chemical industry, and therefore it seems to be the most suitable method to reduce carbon dioxide emissions.

The method consist in dissolving gas in a liquid; it is possible when the mass movement coincides with a chemical reaction. It can be divided into two stages [1]:

- separating one or more components from the gas phase;
- obtaining a particular component in the liquid phase.

Carbon dioxide sequestration by means of this method is based on reactions which are reversible with heat brought from the outside and which take place between other substances. A diagram of the system is presented in Fig. 1 [2].

2 Characteristics of the preliminary cycle

Figure 2 presents a diagram of the preliminary cycle which was analyzed with a view to integrate the carbon dioxide capture system. The fuel driving the system were hard and brown coal with the calorific value 23 MJ/kg and 7.75 MJ/kg, respectively. The cycle is equipped with 4 low- and 3 high-pressure regenerative exchangers, as well as a steam attemperator. The feed water pumps are driven by electric motors. Parallel cooling for the condensers was adopted.

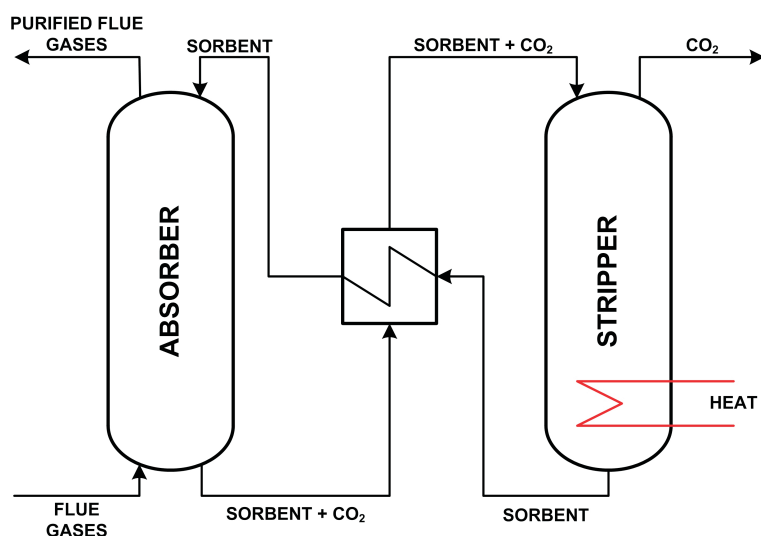


Figure 1. Diagram of the absorber-stripper system [2].

The number of steam outlets from the turbine was determined on the basis of the outlet velocity in the last stage of the low pressure part (LP), whose cross-section is 9.7 m^2 . Such cross-sections are used in the turbines of the Polish supercritical power units. For four outlets (two double-flow LP parts) and the pressure in the condenser of 5 kPa, the velocity will be of approx. 250 m/s. The value is included in the range of 150–300 (330) m/s, which values are adopted for turbine construction. If the pressure in the condenser is 4 kPa, the option with six outlets from the LP part should be considered because in this case the outlet velocity exceeds 300 m/s. Table 1 presents the indices of the power unit operation for nominal parameters. A computational analysis was performed using a custom-made analysis code. In order to determine the indices of the power unit operation (Tab. 1), the following values were defined:

- cycle efficiency:

$$\eta_{th} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = \frac{N_i - N_p}{\dot{Q}_{in}},$$

$$\dot{Q}_{out} = \dot{Q}_{con} + \dot{Q}_{ex} + \dot{Q}_p,$$

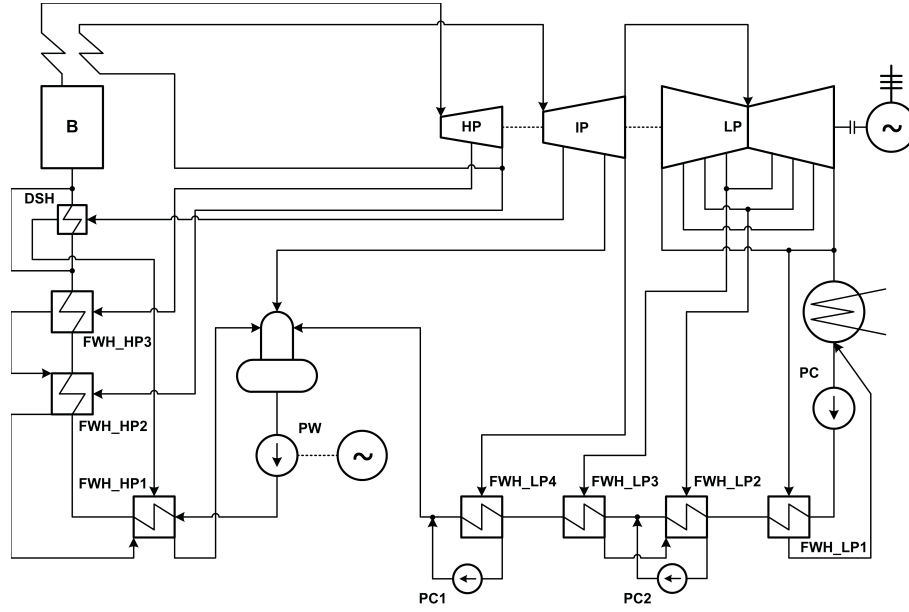


Figure 2. Diagram of the preliminary cycle (B – boiler, HP – high pressure part, IP – intermediate pressure part, LP – low pressure part, FWH – feed water heater, DSH – desuperheater, PC – condensate pump, PW – water pump).

where:

- N_i – steam turbine internal power capacity,
- N_p – work of pumps PC, PW, PC1, PC2
- \dot{Q}_{out} – extracted heat flux,
- \dot{Q}_{con} – heat flux carried away in the condenser,
- \dot{Q}_{ex} – heat losses in regenerative exchangers,
- \dot{Q}_p – heat losses in live- and reheated steam pipelines,
- \dot{Q}_{in} – heat flux in the boiler;

- electricity generation efficiency (gross and net):

$$\eta_{elG} = \frac{N_{elG}}{\dot{Q}_{ch_en}},$$

$$N_{elG} = N_i \eta_m \eta_g,$$

$$\dot{Q}_{ch_en} = \frac{\dot{Q}_{in}}{\eta_b},$$

$$\eta_{elN} = \frac{N_{elG} - N_{pw}}{\dot{Q}_{ch_en}},$$

where:

- N_{elG} – gross electric power,
- N_{pw} – own needs power capacity (7.5% of the gross electric power was assumed),
- \dot{Q}_{ch-en} – fuel chemical energy,
- η_b – boiler efficiency,
- η_g – generator efficiency,
- η_m – mechanical efficiency;

- unit heat consumption:

$$q = 3600 \frac{Q_{in}}{N_{elG}} ;$$

- unit consumption of the fuel chemical energy:

$$q = 3600 \frac{Q_{ch-en}}{N_{elG}} .$$

Table 1. Indices of the 900 MW power unit operation.

No.	Value	Unit	Value	
			Hard coal	Brown coal
1	Heat generated in the boiler	MW	1732.19	
2	Electric power (gross)	MW	900.19	
3	Cycle efficiency	%	50.92	
4	Electricity generation efficiency (gross)	%	49.06	46.32
5	Electricity generation efficiency (net)	%	45.38	42.85
6	Unit heat consumption	kJ/kWh	6927.30	
7	Unit consumption of the fuel chemical energy	kJ/kWh	7337.40	7771.50
8	Outlet velocity from the last stage of the LP part (4 outlets)	m/s	251.24 for pressure $p_k = 5$ kPa 305.63 for pressure $p_k = 4$ kPa	
9	Flue gas mass flow	kg/s	833.36	1104.53
10	CO ₂ mass flow in flue gases	kg/s	176.34	217.70

3 Determination of heat extraction location for the carbon dioxide capture system

The process of carbon dioxide chemical absorption, or desorption – to be precise, is very energy-consuming. In the studies gathered in [3], the amount of

heat necessary to separate 1 kg of CO₂, which is 4.7 MJ/kg of CO₂ for MEA (monoethanolamine) and 2.45 MJ/kg of CO₂ for ammonia was determined. The research is now being conducted to reduce these values. New sorbents which are mixtures of amines are being looked for and the absorber – stripper system is being optimized. It is stated in [4] that the amount of heat can be reduced to 2.83 MJ/kg of CO₂ for MEA. The research conducted at the RITE (Research Institute of Innovative Technology for the Earth) assumes the reduction in the heat to 2 MJ/kg of CO₂ for MEA, and the development of synthetic amines for which the heat is definitely lower [5]. The amount of heat that has to be generated for desorption to capture 1 kg of CO₂ is presented in Fig. 3 for different sorbents [3–5].

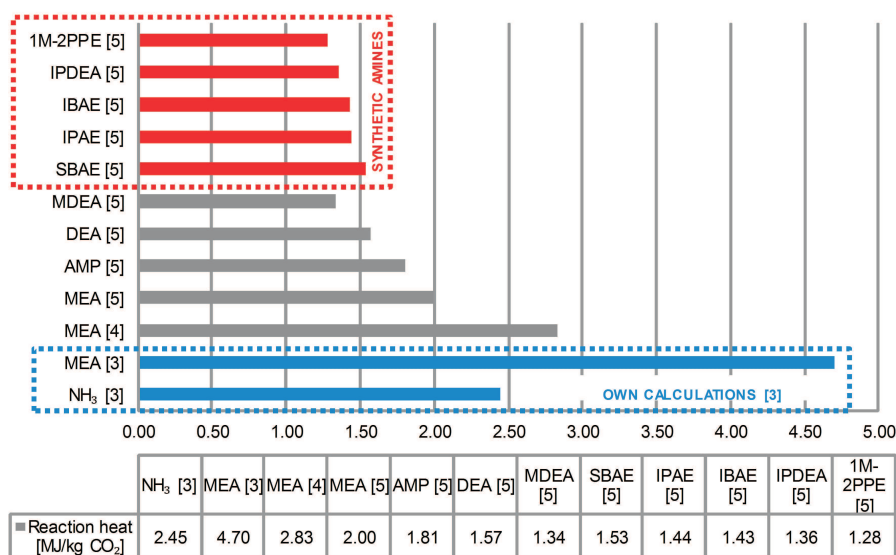


Figure 3. Heat amount needed for sorbent regeneration [3–5].

Table 2 presents the share of heat needed to separate 1 kg of CO₂ compared to the total heat delivered to the cycle shown in Fig. 2. In order to regenerate the applied sorbent, the mixture of the sorbent and CO₂ has to be heated to the appropriate temperature. For the aqueous solution of MEA, the regeneration temperature is 125 °C (which corresponds to saturation pressure of 0.232 MPa), whereas for ammonia it is 157 °C (saturation pressure – 0.572 MPa).

The steam extracted from the turbine can be the source of heat needed for the separation system. For such large amounts of steam, the only possible place of extraction is the air chamber between the IP and LP parts. In order to maintain

the constant pressure value of the steam feeding the capture system, it is necessary to build a choke at the inlet to the LP part (Fig. 4).

Table 2. The share of heat needed for sorbent regeneration compared to the heat generated in the boiler.

Sorbent	Heat needed to capture 1 kg of CO ₂ [MW]	The share of heat needed for separation in the heat generated in the boiler [%]	
		Hard coal	Brown coal
MEA	2.00	20.36	25.13
	2.83	28.81	35.56
	4.70	47.85	59.07
NH ₃	2.45	24.94	30.79

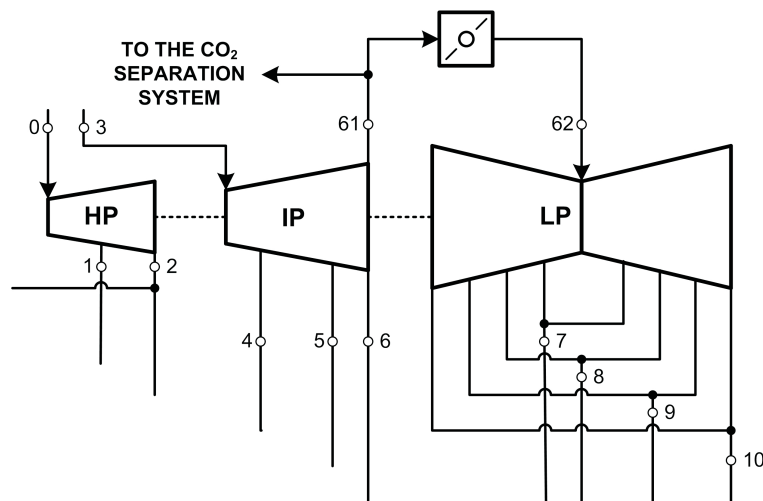


Figure 4. Diagram of the turbine with a fitted choke.

Table 3 presents the steam parameters at the selected turbine bleeds for the configuration adopted as the preliminary one. It should be noted that at the outlet from the IP part (point 6 in the chart, Fig. 5) the steam parameters are insufficient to feed the separation system with ammonia as the sorbent. In this case, the expansion line in the IP part should be shifted from point 6 to point 5a (Fig. 5). The IP part would have a smaller number of stages, while more stages would have to be added to the LP part. For MEA, the parameters of this steam

are too high. They can be reduced at a reducing and cooling station, or the turbine design must be rebuilt. In the latter case, extra stages should be added at the outlet from the IP part and the initial stages in the LP part should be removed. The expansion line end point in the IP part would then be shifted from point 6 to point 61, and in the LP part the expansion line would be shortened.

Table 3. Steam parameters at selected turbine bleeds.

Bleed number	Steam pressure [MPa]	Steam temperature [°C]	Saturation temperature [°C]
5	1.173	670.00	186.94
6	0.574	316.89	157.51
7	0.250	227.82 <td 127.41	
8	0.093	138.04	97.59

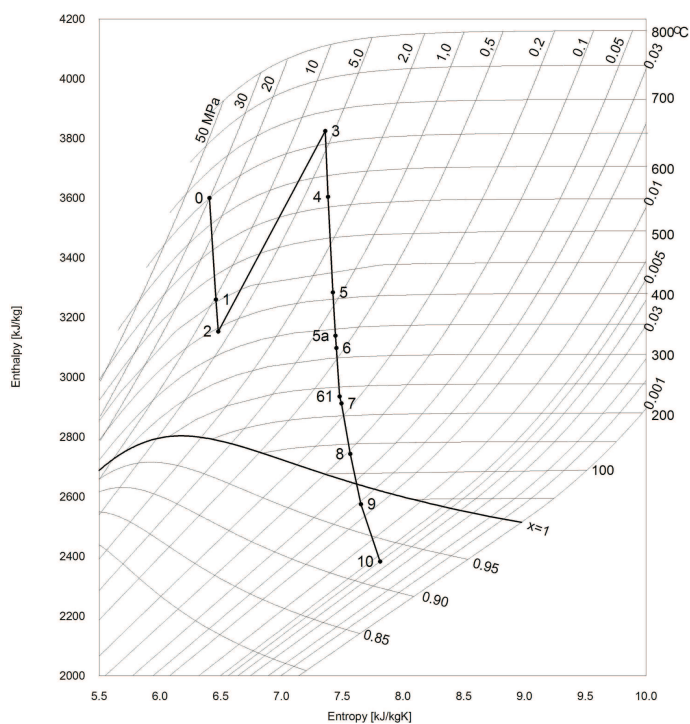


Figure 5. The line of expansion in the turbine.

4 Integration of the carbon dioxide separation system

The subject of the analysis is a cycle integrated with a CO₂ separation system with a structure similar to the preliminary system designed for a particular sorbent. It is assumed that the sorbents will be aqueous solutions of MEA or NH₃ with heat necessary for regeneration as shown in Tab. 2. The steam reaching heat exchanger HE_CCS (Fig. 6) is extracted from the turbine air chamber, and, after releasing heat, the condensate is introduced into the main cycle. Figure 6 presents the possible variants of condensed steam re-entering the cycle. Variant 1 assumes that the condensed steam will be pumped to the node between regenerative exchangers FWH_LP3 and FWH_LP4. Variant 2 assumes that the condensate will return to the deaerator. Such a choice of locations has been determined by the outlet parameters of the condensate directed to the cycle. It is assumed that the difference in temperature in heat exchanger HE_CCS will be 5 K.

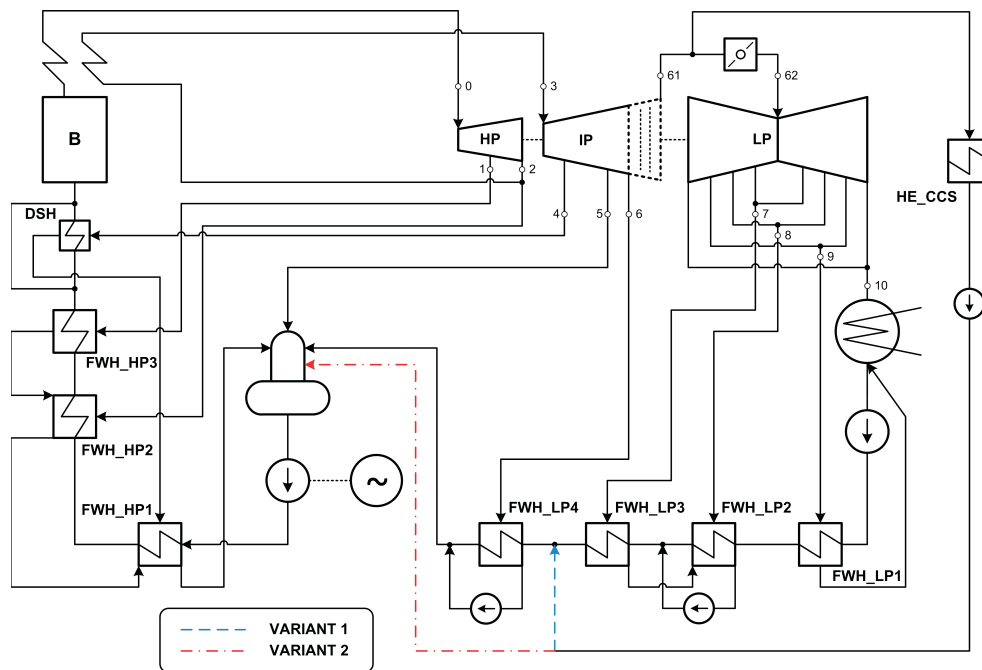


Figure 6. Diagram of the preliminary configuration with variants of the condensate re-entering the cycle (B – boiler, HP – high pressure part, IP – intermediate pressure part, LP – low pressure part, FWH – feed water heater, DSH – desuperheater, PC – condensate pump, PW – water pump, HE – heat exchanger).

Figures 7 and 8 present changes in the efficiency of electricity generation depending on the varying demand for regeneration heat, kind of fuel and the condensate re-entering the cycle. It is worth noting that the change in efficiency for different places at which the condensate re-enters the cycle varies within range of 0.04–0.12 pp, while the change in electric power presented in Figs. 9 and 10 pp is from 0.03 to 2.5 MW.

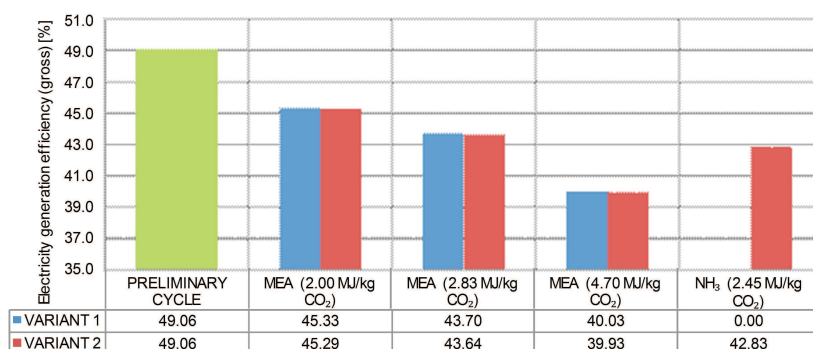


Figure 7. Change in electricity generation efficiency depending on heat needed for separation of 1 kg of CO₂ – hard coal.

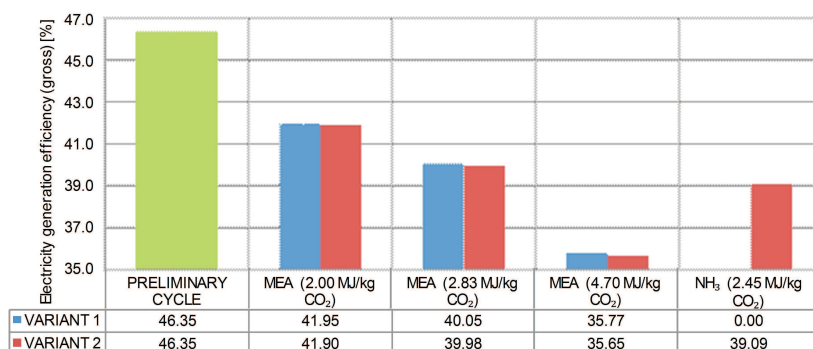


Figure 8. Change in electricity generation efficiency depending on heat needed for separation of 1 kg of CO₂ – brown coal.

The impact of the change in the values of heat needed for the capture system with MEA as the sorbent on the power unit efficiency has also been analyzed (Fig. 11). The analysis shows that a reduction by 1 MJ/kg of CO₂ causes a rise in the efficiency by approx. 2 percentage points.

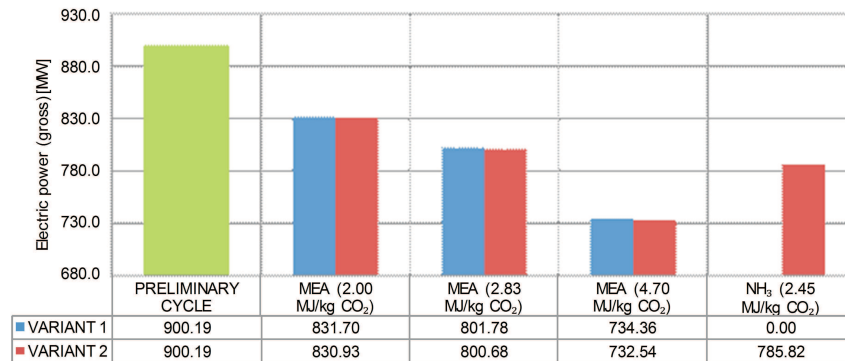


Figure 9. Change in electric power depending on the amount of heat needed for separation of 1 kg of CO₂ – hard coal.

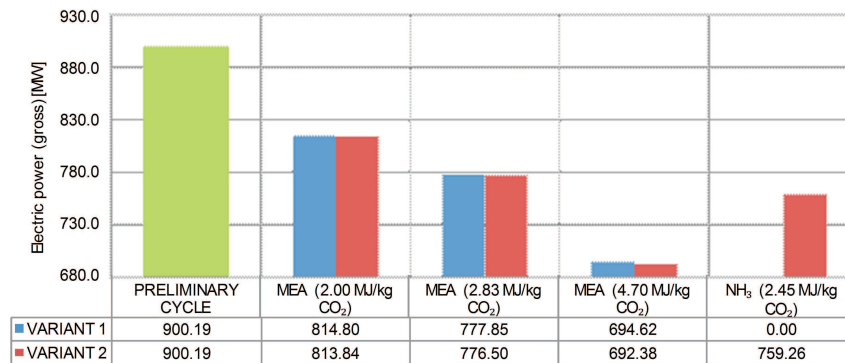


Figure 10. Change in electric power depending on the amount of heat needed for separation of 1 kg of CO₂ – brown coal.

5 Conclusion

The integration of the CO₂ capture system using chemical absorption is very energy-consuming. At the moment, research is being conducted to reduce the demand for heat necessary for the sorbent regeneration. With the sorbents now in use, the fall in the electricity generation efficiency is approx. 10 pp in the case of MEA and approx. 7 pp in the case of ammonia. The fall in power amounts to approx. 20% and 14%, respectively. In reality, the decrease in efficiency and power is bigger, because the CO₂ compression has to be taken into account. The reduction in the heat needed for CO₂ separation by 1 MJ/kg of CO₂ will produce

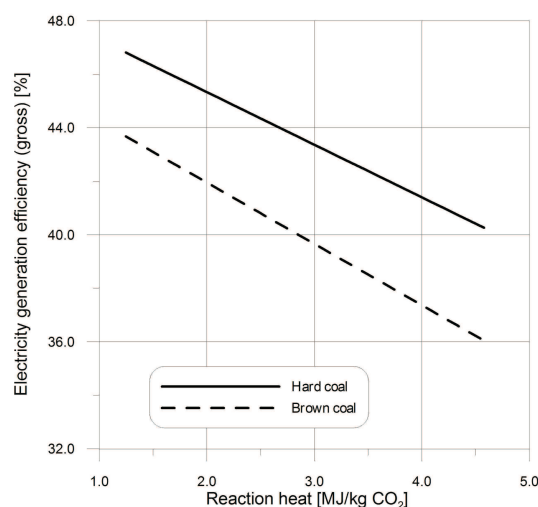


Figure 11. Decrease in efficiency depending on the change in the amount of heat needed for the CO₂ capture system.

a rise in the power unit efficiency by approx. 2 percentage points.

The choice of the location at which condensed steam is introduced into the main cycle (between LP3 and LP4) indicates that this is a more advantageous solution compared to the discharge into the deaerator. The change in efficiency, however, is very small and varies within a range of 0.04–0.12 percentage points. The fall in power value is from 0.03 to 2.5 MW.

Heat extraction into the separation system makes it absolutely necessary to redesign the steam turbine (the IP and LP parts), as well as the regenerative system. For the preliminary configuration under analysis, extra stages should be added to the IP part, and the initial stages in the LP part should be removed if MEA is the sorbent. If ammonia is used, the final stages of the IP part should be removed in order to raise the values of the outlet parameters of this part.

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Analiza możliwości poboru pary z turbiny bloku kondensacyjnego 900 MW do instalacji separacji CO₂

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

Przedstawiono wymagania instalacji separacji CO₂ metodą absorpcji chemicznej w zakresie ilości ciepła oraz parametrów czynnika grzejącego, potrzebnego do regeneracji sorbentu. Analizowano możliwości poboru pary z turbiny do zasilania instalacji separacji CO₂. Określono wskaźniki pracy bloku dla różnych sorbentów. Przedstawiono możliwości przebudowy turbiny po zintegrowaniu bloku z instalacją separacji oraz związane z tym zmiany w układzie regeneracji. Analizowano wpływ przyjętej konfiguracji części niskoprężnej turbiny na zakres jej przebudowy. Obliczenia zostały przeprowadzone dla nadkrytycznego kondensacyjnego bloku węglowego o mocy 900 MW opalanego węglem kamiennym lub brunatnym. Analizowano również możliwości poboru ciepła do instalacji separacji ze spalin wylotowych z kotła.